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Spatial Optimization Methodology for Lighting Infrastructure Targeting Criminal Behavior Prevention: A Case Study of Closed Non-Gated Residential Areas

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Spatial Optimization Methodology for Lighting Infrastructure Targeting Criminal Behavior Prevention: A Case Study of Closed Non-Gated Residential Areas

Abstract: With the acceleration of urbanization, the importance of crime prevention in aging residential areas has become increasingly prominent, as improper spatial distribution of streetlights significantly weakens security effectiveness. This study proposes a crime prevention-oriented spatial optimization method for lighting facilities, focusing on enclosed but non-gated residential areas. By quantitatively modeling the lighting matrix, the study innovatively achieves refined spatial planning. First, a crime prevention demand-oriented lighting requirement matrix is constructed based on a road classification model. Second, a lighting resource allocation matrix is generated through spatial simulation of the light environment. Finally, a multi-objective optimization model is established to minimize illumination differences at the grid level. The genetic algorithm results indicate that, compared to traditional layouts, the optimized scheme effectively enhances the coverage of lighting with crime deterrence effects while balancing cost efficiency and crime risk reduction. This paradigm provides a generalizable methodological framework for urban security governance in lighting planning.

Keywords: Closed non-gated residential areas; Crime prevention; Lighting facility layout; Lighting expectation matrix; Lighting resource allocation matrix

1 Introduction

1.1 Lighting Layout and Crime Prevention

According to the CPTED (Crime Prevention Through Environmental Design) theory, natural surveillance and target hardening measures have significant effects on crime prevention [2][3]. The theory of natural surveillance aims to enhance natural visual monitoring through environmental design, thereby increasing safety and reducing criminal activities. The core elements of natural surveillance include visual visibility, activity and medium, boundary clarity, community involvement, etc. [9]. Target hardening refers to the implementation of protective measures around crime targets, making criminal activities more difficult, dangerous, time-consuming, or less likely to succeed, thus reducing the likelihood of crime [10]. A good lighting layout improves the visibility of public areas, increasing the likelihood of "witnesses" and making criminals feel more at risk of being watched, thereby reducing their criminal intent. Additionally, increased lighting eliminates shadows and dark corners, reducing the opportunities for criminals to hide and approach targets, and increasing their risk of being discovered and caught. For example, Aaron Chalfin installed varying amounts of lighting fixtures in 40 public housing communities in New York and collected crime data for six months after the installation. The analysis found that lighting can reduce the crime rate in communities [28]. Donghyun Kim integrated lighting standards and CPTED guidelines in three communities in South Korea, installed more safety lights, and adjusted the direction of existing lighting to improve the lighting environment and enhance community safety [29]. Cho Y developed an intelligent security lighting system based on the CPTED concept, which automatically turns on more lights when pedestrians pass by, enhancing the sense of security and deterring potential crimes [30]. In summary, a good lighting layout plays a crucial role in crime prevention and is an important means of enhancing public safety and reducing criminal activities.

1.2 Current Research Status on Lighting Facility Layout Optimization

According to the above theories, good lighting facilities play a positive and effective role in crime prevention. However, there are many issues with the lighting facilities in old residential areas in China, such as outdated lighting equipment, unreasonable layout, untimely maintenance, low energy efficiency, and lack of intelligent management [4][19]. Residential areas without access control systems lack passage control to inhibit outsiders from entering the community [20], resulting in a weak sense of territoriality and a higher susceptibility to crime [8]. On one hand, these issues are due to the early planning of old residential areas in China, where lighting facility planning was simple and crude, lacking consideration for environmental crime prevention. On the other hand, as the operational time of residential areas extends, the inability to timely follow up with maintenance and updates raises spatial security risks [3]. Therefore, the optimization and renovation of lighting facilities in old residential areas are urgently needed [14].

Currently, most research on crime prevention is based on the CPTED theory, environmental psychology theory, and criminology theory [15], focusing on urban residential street environments. In designing lighting facilities, the focus is on the illumination requirements of individual lighting facilities, the coverage area of the lighting environment [4], and assessing the impact of different lighting environments on people's behavior and emotions [6][7]. For example, by increasing the number and spatial arrangement of lighting facilities, improving lighting quality, controlling light color, and timely maintenance, night-time criminal behavior can be suppressed [21]-[24]. Alternatively, by using low light sources, controlling light beams, avoiding glare, and increasing easy-to-read lighting

facilities, the lighting conditions can be improved to create a safer lighting environment [5]. However, these methods only focus on the design optimization of the lighting facilities themselves [16], without considering the correlation between the entire crime process and the optimization of lighting facility layout.

Crime is a process behavior with a trajectory, but in conventional GIS analysis, this process is simplified, and only the association between crime points and lighting facility points is analyzed. This makes the above methods insufficient to fully consider the impact of lighting facilities on criminals' behavior during the target-searching process [18]. On the other hand, research on optimizing lighting facility layout in China has only proposed strategies for controlling the illumination area, lacking consideration of the logic of criminal behavior. In particular, there is a lack of research on the relationship between lighting facility layout and crime occurrence and escape path selection. This results in lighting facility layouts for crime prevention in China remaining within static and isolated planning thinking [8].

In response to this issue, this paper proposes an optimized lighting facility layout method for crime prevention. This method is based on the expected lighting resource allocation matrix and the lighting resource contribution matrix. Combined with a genetic algorithm, it quantitatively analyzes lighting resources to more reasonably and effectively allocate lighting facilities, achieving an optimized lighting facility layout.

1.3 Research Approach of This Paper

First, to facilitate the construction of matrices and simplify the calculation process, the residential area plane is gridded. Then, based on the road classification results of the residential area, the expected lighting resource allocation matrix for each residential area is established, and the lighting resource contribution matrix is established based on the lighting facility simulation results.

Then, based on these two matrices, an initial lighting facility optimization model is derived by setting the minimization of the difference between the expected lighting resource allocation matrix and the lighting resource contribution matrix as the objective function. The example is substituted into the optimization model and solved using a genetic algorithm.

Next, after determining the layout principles for candidate lighting facility points, an optimized lighting facility layout plan for closed non-gated residential areas is constructed based on the aforementioned optimization model, aiming to reasonably allocate lighting resources in the residential area.

Finally, to verify the effectiveness of the optimization model, the optimized results are evaluated from three aspects: uniformity index - overall illumination compliance rate of the residential area; focus index - illumination compliance rate of key areas; and economic index - construction of lighting facilities per unit area of compliant illumination. The effectiveness of the optimized lighting facility layout model for residential areas constructed in this paper is verified.

Based on the above research approach, the technical route for establishing an optimized lighting facility layout model for crime prevention is shown in the following diagram:

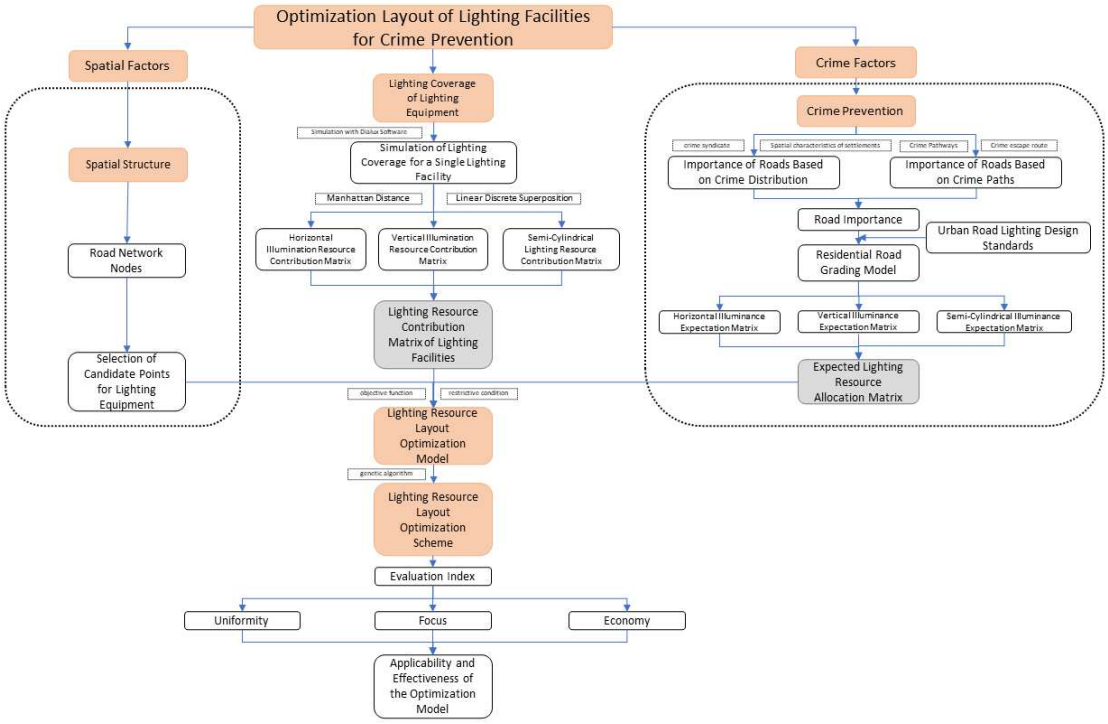


Fig1 Technology Roadmap

2.Establishment of the Lighting Facility Layout Optimization Model

2.1 Grid Processing

Grid processing of three-dimensional space typically involves dividing the space into a series of small, regular cells (usually cubes). These cells form a grid. While the illumination range of lighting facilities is complex, converting spatial problems into planar ones and using grid processing can simplify calculations and reduce data complexity. Before establishing the lighting resource allocation matrix for the residential area, the map needs to be grid-processed. This grid processing uses regular grids, where the space is evenly divided into equally sized cubic cells. Incomplete grids are considered only if their area exceeds half of a complete grid; otherwise, they are disregarded. In practice, first determine the side length a (in meters) of each small grid, and then divide the residential area into m×n grids with a side length of a. Each small grid in the i-th row and j-th column is denoted as Aij, and the center of the grid is used as the installation point for the lighting facility, denoted as Oij.

2.2 Establishing the Expected Lighting Resource Allocation Matrix

2.2.1 Illuminance

Illuminance refers to the amount of luminous flux received per unit area, reflecting the degree to which a surface is illuminated. The unit of illuminance is lux, where 1 lux equals 1 lumen per square meter of luminous flux. In simple terms, illuminance describes the intensity of light on a surface, commonly used to assess the quality and effectiveness of environmental lighting.

When pedestrians walk at night, it is first necessary to ensure the visibility of the road surface to ensure traffic safety. The average horizontal illuminance of the road surface and the minimum horizontal illuminance of the road surface represent the visibility of the road surface. In addition, to quickly identify oncoming pedestrians, the pedestrian's face (approximately 1.5m height) needs sufficient vertical illuminance and semi-cylindrical illuminance. Since pedestrians' walking speed is much lower than that of vehicles, they have more adaptation time to brightness changes, and glare has less impact on pedestrians. However, uncomfortable glare can still cause interference. Field

surveys have found that residential lighting is generally insufficient, and uncomfortable glare rarely occurs, so the glare index is not used as an evaluation indicator. In summary, this paper selects the average horizontal illuminance of the road surface, the minimum horizontal illuminance of the road surface, vertical illuminance, and semi-cylindrical illuminance as simulation and measurement parameters. The meanings and calculation methods of these parameters are as follows:

The schematic diagram of the lamp illuminance calculation is as follows:

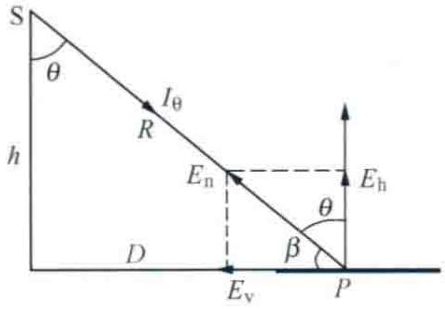


Fig2.1 Illuminance

Horizontal illuminance calculation formula:

$$E_h = \frac{I_\theta}{R^2}\cos\theta$$

Where:

E_h— Horizontal illuminance at point **P** on the horizontal plane **H** produced by point light source **S**, in lux (lx);

I_ϑ — Luminous intensity of the point light source in the direction of illumination, in candela (cd);

R — Distance from the point light source to the calculation point on the illuminated surface, in meters (m);

cosϑ — Cosine of the angle between the normal to the illuminated surface through point light source **S** and the incident light ray.

Vertical illuminance formula:

$$E_v = \frac{I_\theta}{R^2}\sin\theta$$

Where:

E_v — Vertical illuminance at point **P** on the vertical plane **V** produced by point light source **S**, its direction parallel to the horizontal plane **H**, in lux (lx);

I_ϑ— Luminous intensity of the point light source in the direction of illumination, in candela (cd);

R — Distance from the point light source to the calculation point on the illuminated surface, in meters (m);

sinϑ — Sine of the angle between the normal to the illuminated surface through point light source **S** and the incident light ray.

Semi-columned illuminance formula:

$$E_{sc} = \sum I(c,\gamma)\,(1+\cos\alpha_{sc})\cos^2\varepsilon\sin\varepsilon\Phi MF\big/\pi(H-1.5)^2$$

Where:

Esc — Maintained semi-cylindrical illuminance at a point in space, in lux (lx);

Σ — Sum of contributions of all light fixtures to the semi-cylindrical illuminance at the calculation point;

I(c,γ) — Luminous intensity in the direction of the calculation point, in candela per kilolumen (cd/klm);

αsc — Angle between the vertical plane containing the intensity vector and the vertical plane perpendicular to the semi-cylindrical plane;

ε — Angle of incidence of the light;

H — Mounting height of the light fixture;

Φ — Initial luminous flux of the light source, in kilolumen (klm);

MF — Maintenance factor of the light fixture.

Average horizontal illumination:

The average horizontal illuminance of the road surface is the average value of the illuminance at various points on the road surface, measured or calculated according to the provisions of the International Commission on Illumination (CIE). Currently, large area lighting measurements primarily use two methods: the center method and the four-point method. The center method places the illuminance meter at the center point of the measurement grid. The four-point method takes measurements at the four corner points of the measurement grid, as illustrated below:

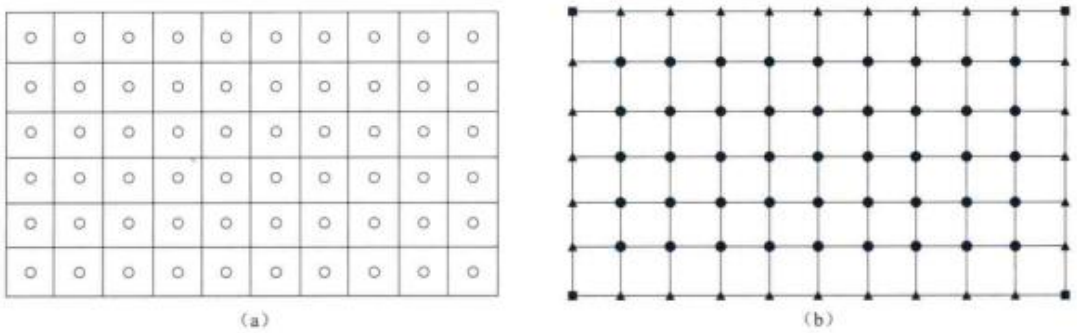


Fig2.2 Average horizontal illumination

(a) Center approach; (b) Four-point approach

The average illuminance is calculated as follows:

(a) The center method:

$$E_{av} = \frac{\sum E_i}{N}$$

Where:

ΣEi——Sum of illuminance at each grid center point, lx;

N——Number of center measurement points;

Eav——Average illuminance, lx.

(b) The four-point method:

$$E_{av} = \frac{1}{4MN}\left(\sum E_a + 2\sum E_n + 4\sum E_s\right)$$

Where:

Eav——Average illuminance, lx;

M, N——Number of measurement points along the length and width of the entire measured plane (generally, the measured area is arranged in a square or rectangular shape);

ΣEa——Sum of illuminance at the four corners of the entire measurement area;

4ΣEs——Sum of illuminance at the measurement points on the four sides of the entire measurement area (excluding the four corner points);

2ΣEn——Sum of illuminance at the remaining measurement points in the entire measurement area.

2.2.2 Illumination expectation matrix

The illuminance expectation matrix refers to the matrix representation of the ideal or expected illuminance levels for different areas within a specific environment or space. This matrix lists the required illuminance values for different areas at different times or usage scenarios, used to guide lighting design and layout. It ensures that the illuminance of each area meets the expected requirements, thereby optimizing lighting effects and energy efficiency.

2.2.3 Road grading model

Considering that crime is a complete process involving three stages: the travel stage from the residential area entrance to the crime target, the stay and crime execution stage at the crime target, and the escape stage from the crime target to the residential area entrance, a residential road importance grading model is established based on the crime behavior process. Firstly, based on geographical spatial effects, an analysis model of the residential area spatial structure is established. With the help of spatial syntax, the spatial characteristics of each unit space are quantified. By comparing and analyzing the crime distribution density map, the spatial characteristics of high and low crime density roads in each residential area are determined. Secondly, based on rational choice theory, a crime path simulation idea is proposed to simulate the paths of criminals corresponding to each crime point in the residential area. Based on the evaluation of the road spatial importance model and the crime path road importance model, it is determined whether each road is a crime path. Finally, based on the process of target search-crime execution-crime escape and corresponding to the four levels of pedestrian roads in the design standard, a road importance grading model is established. Based on the road grading model and the urban road lighting design standard, an expected illuminance distribution matrix is established, as shown in the figure.

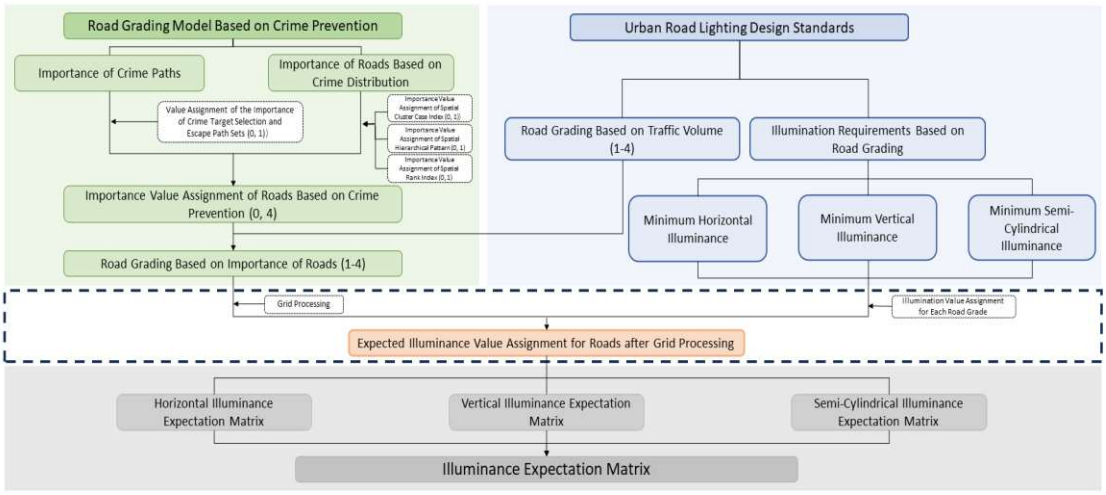


Fig2.3 Road grading model diagram

This study investigates the relationship between lighting and criminal activity by introducing a hierarchical road model to analyze the association between different road classifications and crime incidents. The results demonstrate statistically significant correlations between specific road types and criminal activities, indicating that road infrastructure plays a critical role in the spatial distribution of crime-prone areas. Based on these findings, implementing targeted lighting optimization in high-correlation road networks—through rational adjustments to lighting intensity and coverage—can effectively enhance nighttime visibility and exert deterrent effects on potential criminal behavior.

2.2.4 Three illuminance expectation matrices:

In Section 2.2.3, we established a grading calculation model for residential roads based on crime prevention. The calculation results correspond to the four pedestrian road levels divided in the "Urban Road Lighting Design Standard." Therefore, this section will establish a residential area expected lighting resource allocation matrix according to the parameter standards in the standard. According to the minimum horizontal illuminance, minimum vertical illuminance, and minimum semi-cylindrical illuminance specified in the standard, an expected lighting resource allocation matrix for the residential area is established.

(1) Horizontal Illumination Expectation Matrix

Establish the road horizontal illuminance expectation matrix Ah based on road grade:

$$A_h = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & A_{ij} & \vdots \\ A_{m1} & \cdots & A_{mn} \end{pmatrix}$$

Among them:

$$A_{ij} = \begin{cases} 3 & \text{The road within the grid is a Level 1 road} \\ 2 & \text{The road within the grid is a Level 2 road} \\ 1.5 & \text{The road within the grid is a Level 3 road} \\ 1 & \text{The road within the grid is a Level 4 road} \\ 0 & \text{The grid location is not within a road area} \end{cases}$$

(2) Vertical illuminance expectation matrix

Establish the road vertical illuminance expectation matrix Bv based on road grade:

$$B_v = \begin{pmatrix} B_{11} & \cdots & B_{1n} \\ \vdots & B_{ij} & \vdots \\ B_{m1} & \cdots & B_{mn} \end{pmatrix}$$

Among them:

$$B_{ij} = \begin{cases} 5 & \text{The road within the grid is a Level 1 road} \\ 3 & \text{The road within the grid is a Level 2 road} \\ 2.5 & \text{The road within the grid is a Level 3 road} \\ 1.5 & \text{The road within the grid is a Level 4 road} \\ 0 & \text{The grid location is not within a road area} \end{cases}$$

(3) Half-column illumination expectation matrix

Establish the road semi-cylindrical illuminance expectation matrix Csc based on road grade:

$$C_{sc} = \begin{pmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & C_{ij} & \vdots \\ C_{m1} & \cdots & C_{mn} \end{pmatrix}$$

Among them:

$$C_{ij} = \begin{cases} 3 & \text{The road within the grid is a Level 1 road} \\ 2 & \text{The road within the grid is a Level 2 road} \\ 1.5 & \text{The road within the grid is a Level 3 road} \\ 1 & \text{The road within the grid is a Level 4 road} \\ 0 & \text{The grid location is not within a road area} \end{cases}$$

It can be observed that the semi-cylindrical illuminance expectation matrix is consistent with the horizontal illuminance expectation matrix.

2.3 Establishment of the lighting resource contribution matrix

2.3.1 Lighting resource contribution matrix

The Lighting Resource Contribution Matrix (LRCM) plays a crucial role in the layout of lighting facilities. By systematically evaluating and optimizing the multi-dimensional impacts of lighting systems, the LRCM guides the design of lighting layouts to achieve the best balance in terms of energy efficiency, environmental impact, human health, and visual effects. Specifically, the LRCM helps to evaluate the energy performance of different layout schemes, optimizing the arrangement of luminaires to ensure maximum use of natural light and reduce energy consumption. Additionally, the LRCM can assess the environmental impact of layout schemes, selecting layouts with low environmental impact to minimize the negative effects of the lighting system on the environment.

In terms of enhancing human health and comfort, the LRCM analyzes light distribution, color temperature, and brightness to design lighting environments that meet health standards and provide comfort. Additionally, the LRCM aids designers in choosing lighting layouts that best highlight architectural features and landscape aesthetics, enhancing both aesthetics and visual effects. In roads and public areas, the LRCM improves public safety by setting appropriate light distribution and

brightness, reducing dark areas and accident rates.

2.3.2 Simulation of individual lighting fixtures

Different types and installation heights of lighting fixtures will have different impacts on lighting resources. Therefore, when establishing the Lighting Resource Contribution Matrix (LRCM), these factors need to be considered and corresponding calculations adjusted. In this study, after determining the type and installation height of the lamps using Dialux software, a sufficiently large rectangular calculation element is drawn. The residential area is divided into small grids, and the lamps are installed at the center of the calculation surface. The horizontal, vertical, and semi-cylindrical illuminance values at the center points of each grid can then be calculated. Based on these data, the horizontal illuminance contribution matrix Gh, vertical illuminance contribution matrix Gv, and semi-cylindrical illuminance contribution matrix Gsc of a single lighting fixture can be obtained.

Taking the horizontal illuminance contribution matrix as an example, select the IP66 product from WE-EF company with an installation height of 4m, and describe in detail the process of establishing the horizontal illuminance contribution matrix for a single luminaire.

Define the horizontal illuminance contribution matrix Gh of a single luminaire as:

$$G_h = \begin{pmatrix} G_{11} & \cdots & G_{1n} \\ \vdots & G_{ij} & \vdots \\ G_{m1} & \cdots & G_{mn} \end{pmatrix}$$

Among them,

G_{ij} represents the contribution value of a single luminaire to the horizontal illuminance in area Aij , which needs to be determined based on simulation results. The simulation results of the horizontal illuminance for a single luminaire of this type are shown in the figure (unit: lx), with the center grid being the luminaire installation location. For grids with horizontal illuminance below 0.1 lx, the contribution value of their horizontal illuminance is counted as 0:

0	0.1	0.2	0.2	0.2	0.1	0
0.1	0.2	1	1.6	1	0.2	0.1
0.2	1	8.7	38	8.7	1	0.2
0.2	1.6	38	160	38	1.6	0.2
0.2	1	8.7	38	8.7	1	0.2
0.1	0.2	1	1.6	1	0.2	0.1
0	0.1	0.2	0.2	0.2	0.1	0

Fig2.4 Simulation of individual lighting fixtures

2.3.3 Lighting Resource Contribution Matrix for Individual Lighting Fixtures

Manhattan Distance, also known as City Block Distance or L1 Distance, is a method for calculating the distance between two points. Its calculation method is based on the total distance moved along the axis directions in a rectangular coordinate system.

In a two-dimensional plane, given two points (X_1, Y_1) and (X_2, Y_2), the formula for calculating the Manhattan distance d is:

$$d = | X_1 - X_2 | + | Y_1 - Y_2 |$$

In a three-dimensional space, given two points (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2), the formula for

calculating the Manhattan distance d is:

$$d = | X_1 - X_2 | + | Y_1 - Y_2 | + | Z_1 - Z_2 |$$

In higher dimensional spaces, this formula can be generalized as:

$$d = \sum_{i=1}^{n} |x_i - y_i|$$

Among them: (X_1, X_2, ..., X_n) and (Y_1, Y_2, ..., Y_n) are the coordinates of two points.

For residential area roads, the maximum value of the minimum horizontal illuminance specified by national lighting standards is 3 lx. To reduce computational load, the grid cells in the simulation results with values greater than or equal to 3 lx are processed and modified to 3 lx. The results are shown in the figure, with the Manhattan distances from each grid cell to the grid cell where the light fixture is installed (i.e., the center grid) also labeled.



Fig2.5 Manhattan distance

It can be found that the horizontal illuminance values of each grid are closely related to the Manhattan distance. Therefore, the Gij can be calculated using the two-dimensional Manhattan distance function:

$$G_{ij} = \begin{cases} 3 & D(A_{ij}, O_{ab}) \leqslant 2 \\ 1 & D(A_{ij}, O_{ab}) = 3 \\ 0.2 & D(A_{ij}, O_{ab}) = 4 \\ 0.1 & D(A_{ij}, O_{ab}) = 5 \\ 0 & Else \end{cases}$$

Among them, $D(A_{ij}, O_{ab})$ is the Manhattan distance from grid A_{ij} to the grid O_{ab} where the lighting facility is installed. It can be found that, except for individual grids, the single lamp horizontal illuminance contribution matrix G_h can better restore the simulation results. When there are multiple lighting facilities in the residential area, some areas may be affected by the radiation of multiple

lighting facilities. The linear discrete superposition method is used to calculate this part. That is, when the grid A_{ij} is radiated by q lighting facilities, the lighting resource of the grid is the sum of the resources provided by q lighting facilities.

$$G_{ij} = \sum_{k=1}^{q} G_{k,ij}$$

The establishment methods for the vertical illuminance contribution matrix G_v and the semi-cylindrical illuminance contribution matrix G_{sc} for a single lighting facility are similar.

3. Establishment and Solution of the Lighting Resource Layout Optimization Model

3.1 Candidate Point Selection

When optimizing the layout of lighting facilities, the distribution of candidate points for lighting facilities should be restricted to meet basic functional design principles, facilitating subsequent model calculation and solution. The main areas within the residential area include road areas, building areas, and green areas. When optimizing the layout of lighting facilities, the following principles should be noted:

First, lighting facilities should not be installed in building areas.

Second, green areas, generally located between roads and buildings, should be avoided for lighting facility installation. On one hand, being close to residential buildings, strong lighting might affect residents' sleep; on the other hand, vegetation can block light, leading to wasted lighting resources.

Third, lighting facilities should preferably be arranged on one side of the road to facilitate underground cable construction and reduce project costs.

3.2 Objective function

In earlier sections, based on road levels, the expected lighting resource allocation matrices for each road in the residential area were established. Simultaneously, lighting resource contribution matrices were developed based on simulation results. To align as closely as possible with practical requirements, the objective is to minimize the difference between the optimized actual horizontal lighting distribution matrix Ph, vertical lighting distribution matrix P_v, and semi-cylindrical lighting distribution matrix P_{sc}, and their corresponding expected matrices A_h, B_v, and Csc. Therefore, the goal is to minimize the difference between the actual lighting resource allocation matrices and the expected lighting resource allocation matrices as the objective function:

$$\min \ \Delta d = \frac{1}{mn}\left(\sum_{i=1}^{m}\sum_{j=1}^{n}|P_{h,ij} - A_{h,ij}| + \sum_{i=1}^{m}\sum_{j=1}^{n}|P_{v,ij} - B_{v,ij}| + \sum_{i=1}^{m}\sum_{j=1}^{n}|P_{sc,ij} - C_{sc,ij}|\right)$$

$$P_h = \sum_{r=1}^{M} S_r G_{h,r}$$

$$P_v = \sum_{r=1}^{M} S_r G_{v,r}$$

$$P_{sc} = \sum_{r=1}^{M} S_r G_{sc,r}$$

Ph is the actual horizontal illuminance contribution matrix of lighting facilities in the residential

area. M is the number of candidate points. Sr is a logical variable: it equals 1 if lighting facilities are installed at the r-th candidate point, and 0 otherwise. $G_{h,r}$ is the horizontal illuminance contribution matrix formed when lighting facilities are installed at the r-th candidate point. Ah is the expected horizontal illuminance matrix for the residential area. Similarly, P_v and P_{sc} are the actual vertical illuminance contribution matrix and semi-cylindrical illuminance contribution matrix of lighting facilities in the residential area, respectively. $G_{v,r}$ and $G_{sc,r}$ are the vertical illuminance contribution matrix and semi-cylindrical illuminance contribution matrix formed when lighting facilities are installed at the r-th candidate point.

3.3 Decision variables

The lighting facility layout optimization model studied in this paper mainly selects the installation positions of lighting facilities. Therefore, there is only one decision variable, which is Sr. Sr represents whether lighting facilities are installed at the r-th candidate point, with values of 0 or 1.

Constraints:

1. There are two possible states for the installation of lighting facilities at each candidate point: Sr can only be 0 or 1.

2. Cost constraint: The number of lighting facilities installed in the residential area is limited by a budget constraint and cannot exceed a certain value.

$$S_r = \{0, 1\} \quad \forall r \in I_M$$

$$\sum_{r=1}^{M} S_r \leq k$$

In the formula: IM represents the set of candidate grids for lighting facilities within the residential area, and k denotes the maximum number of lighting facilities that can be installed in the residential area.

3.4 Genetic algorithm to solve the optimization model

Genetic algorithms are an optimization method that simulates the process of biological evolution by mimicking mechanisms such as natural selection, crossover, and mutation to search for the optimal solution in the solution space. Genetic algorithms typically include steps such as initializing the population, evaluating fitness, selection, crossover, and mutation. By iteratively applying these steps, genetic algorithms can search for better solutions in the solution space. This method is particularly effective in handling complex optimization problems when the solution space is large or lacks a clear mathematical form[17]. This paper uses genetic algorithms to solve the lighting facility optimization model, which has significant advantages, including strong global search capabilities, suitability for complex and nonlinear problems, high flexibility and adaptability, parallel processing capability, robustness, adaptability to dynamic changes, and ease of integration with other optimization techniques[11]. These advantages enable genetic algorithms to effectively solve lighting facility optimization problems in practical applications, achieving the goals of optimizing lighting effects, reducing energy consumption, and improving economic efficiency.

4. Example Verification

A closed non-gated residential area refers to a residential zone with overall enclosed characteristics but lacking traditional access control management. Such communities typically feature physical boundaries like perimeter walls or vegetative barriers, creating spatial separation from surrounding environments without implementing strict access control systems (e.g., card entry, household registration checks, or guarded gates) to restrict entry/exit. These areas possess practical research value for crime reduction studies due to their insufficient security measures. To verify whether the computational results of the proposed optimization model align with expected

objectives, we selected closed non-gated residential area I as a case study for validation. Covering 12.22 hectares, Community I features complex road networks with interconnected routes, making it an appropriate candidate for testing model effectiveness. The verification procedure comprises the following steps:

First, we gridded the residential area and assigned values to each grid to form the expected lighting resource distribution matrix for the residential area. Specifically, by dividing the area into several small grids, we can precisely define the lighting needs of each region, thereby establishing a detailed model of expected lighting resource distribution.

Meanwhile, according to the principles for selecting candidate points for lighting facilities, we determined the candidate point matrix for lighting facilities in District I. The principles for selecting candidate points comprehensively consider the location of existing facilities, regional population density, and potential safety hazards, ensuring that the candidate points can optimally meet the lighting needs of the residential area.

Finally, we imported the processed relevant data into the optimization algorithm for solving. Through the iterative calculations of the genetic algorithm, we obtained the optimal layout scheme for lighting facilities, ensuring the rational distribution and efficient utilization of lighting resources.

4.1 Gridding the Residential Area Plan

The plan of Residential Area I has an irregular shape, so it was completed into a rectangle with a length of 468m and a width of 280m. For ease of calculation, the direction of the plan was adjusted during gridding, and it was ultimately divided into 117*70 small grids, each with a side length of 4m. The division results are shown in the figure.



Fig4.1. Gridding the Residential Area Plan

4.2 Residential Area Expected Lighting Resource Allocation Matrix

In the previous section, we proposed a grading calculation model for residential roads based on the spatial distribution of crimes and analysis of criminal travel paths. Using the I residential area as an example, we performed a calculation analysis and graded the roads within the I residential area. Based on these grading results and following the method for establishing the expected lighting resource allocation matrix described in the paper, we established the expected lighting resource

allocation matrix for the I residential area.

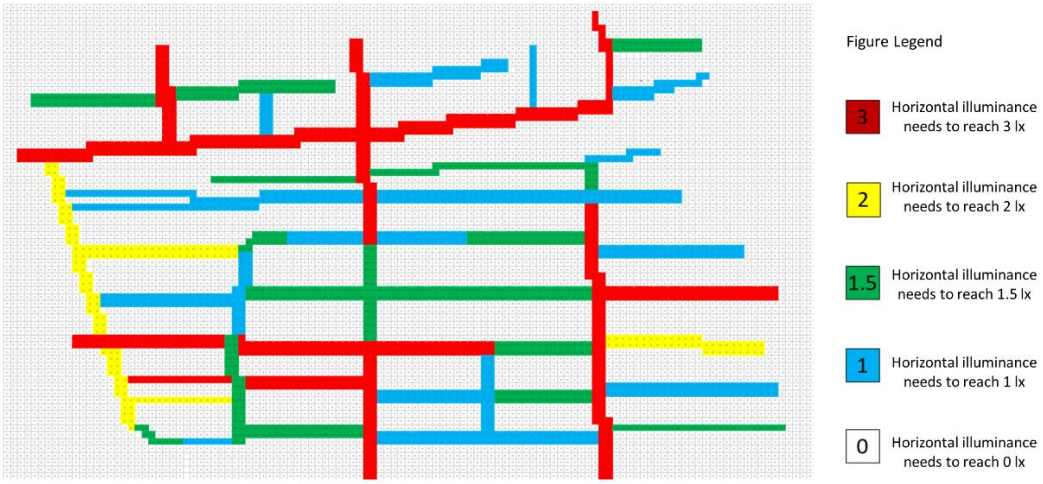


Fig4.2 Horizontal Illumination Expectation Matrix

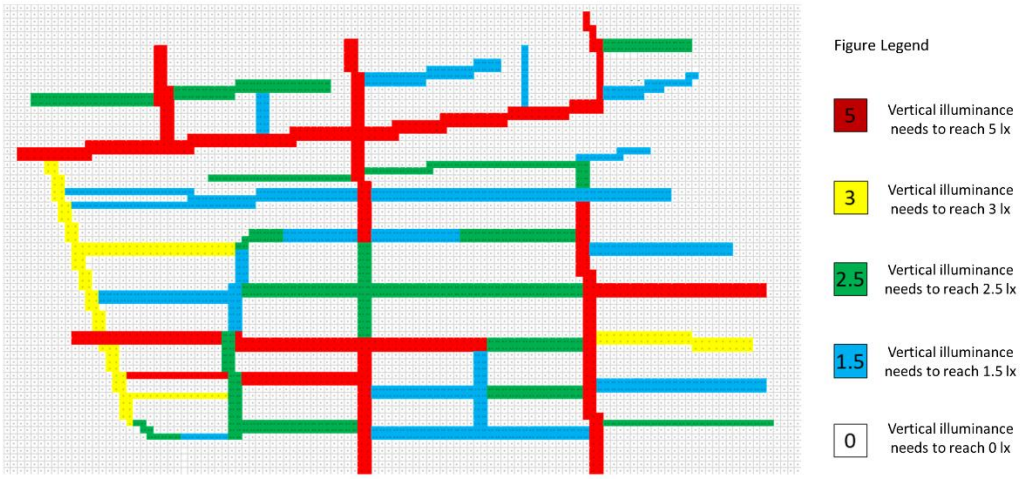


Fig4.3 Vertical Illumination Expectation Matrix

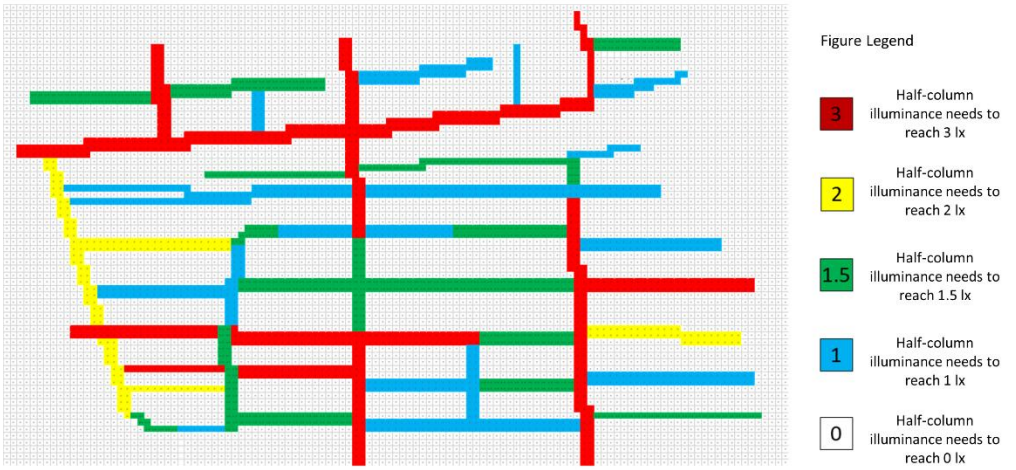


Fig4.4 Half-column illuminance expectation matrix

4.3 Residential Lighting Facility Candidate Point Matrix

According to the principles of selecting lighting facility candidate points, the matrix of lighting facility candidate points for residential area I has been determined, as shown in the figure.



Fig4.5 Lighting Candidate Point Matrix

4.4 Optimization of the layout of lighting facilities in settlements

Using a genetic algorithm to solve the lighting facility layout optimization model for Area I, the parameter settings are as follows:

(1) Chromosome encoding: Area I has a total of 1000 lighting facility candidate points, so the chromosome is set as a 1000-bit binary string.

(2) Parameter settings: The population size is set to M=100, the maximum number of iterations is 200, the crossover probability Pc=0.6, and the mutation probability Pm=0.06. The initial population is generated using the random number method.

(3) Calculation and result generation: After setting the parameters, calculation and solving can be performed. When the termination criteria are met, the optimal solution is output as the layout plan.

The final optimized lighting facility layout plan for Area I is shown in the figure, with a total of 120 lighting facilities:



Fig4.6 Optimization plan for the layout of lighting facilities

4.5 Evaluation indicators

To verify the effectiveness of the optimization model, we use two standards: reducing crime rates and achieving economic efficiency. Specifically, the optimization results are evaluated from three aspects. First, the uniformity indicator—the overall illumination qualification rate of the residential area; second, the focus indicator—the illumination qualification rate of key areas; third, the economic indicator—the cost of constructing lighting facilities per qualified illumination area. Uniformity and focus aim to enhance natural surveillance and target hardening to achieve crime prevention, while economic efficiency considers construction costs to improve the feasibility of the optimization scheme. The meaning and calculation methods of each indicator are as follows:

(1) Overall illumination qualification rate of the residential area:

For residential areas, residents have the need to travel or engage in activities at night. Good horizontal illuminance can ensure ground visibility, improving traffic safety and activity comfort. At the same time, good vertical illuminance and semi-cylindrical illuminance can ensure pedestrians promptly identify the identity and intentions of others, allowing them to prepare accordingly. Therefore, based on the qualification rates of horizontal illuminance, vertical illuminance, and semi-cylindrical illuminance, the overall illumination qualification rate indicator for residential areas is established. Its calculation formula is as follows:

$$Ps = \frac{1}{3}\left(\frac{n_1 + n_2 + n_3}{N_r}\right)$$

In the formula: N_r is the total number of grids in the road area of the residential area, n_1 is the number of grids in the road area that meet the standard horizontal illuminance requirements, n_2 is the number of grids in the road area that meet the standard vertical illuminance requirements, and n_3 is

the number of grids in the road area that meet the standard semi-cylindrical illuminance requirements.

(2) Illumination qualification rate of key areas

The lighting facility layout optimization model proposed in this study aims to reduce crime and improve the safety of residential areas. Therefore, the illumination qualification rate of key areas is proposed as a safety indicator, calculating the illumination qualification rate of crime-prone road spaces in the residential area to verify the safety of the optimized lighting environment. The calculation formula is as follows:

$$Ps_k = \frac{1}{3}\left(\frac{n_{k1} + n_{k2} + n_{k3}}{N_{kr}}\right)$$

In the formula: N_{kr} is the total number of grids in the first-level road area of the residential area, n_{k1} is the number of grids in the first-level road area that meet the standard horizontal illuminance requirements, n_{k2} is the number of grids in the first-level road area that meet the standard vertical illuminance requirements, and n_{k3} is the number of grids in the first-level road area that meet the standard semi-cylindrical illuminance requirements.

(3) Construction cost of lighting facilities per unit qualified illumination area

Economic benefits are essential factors to consider in optimizing the layout of lighting facilities. Pursuing safety without regard to cost is obviously impractical. Therefore, this paper proposes the construction cost of lighting facilities per unit qualified illumination area as an economic indicator to verify the economic viability of the optimization results. The calculation formula is as follows:

$$UC = \frac{3C}{n_1 + n_2 + n_3}$$

In the formula: C is the total construction cost of the lighting facilities, n_1 is the number of grids in the road area that meet the standard horizontal illuminance requirements, n_2 is the number of grids in the road area that meet the standard vertical illuminance requirements, and n_3 is the number of grids in the road area that meet the standard semi-cylindrical illuminance requirements.

4.6 Analysis of the results of the optimization of the layout of the lighting facilities - the example of settlement I

The optimized lighting facility layout points were input into Dialux for simulation. The overall lighting simulation of I residential area, along with the results and pseudo-color maps of horizontal illuminance, vertical illuminance, and semi-cylindrical illuminance, are shown in the figure.

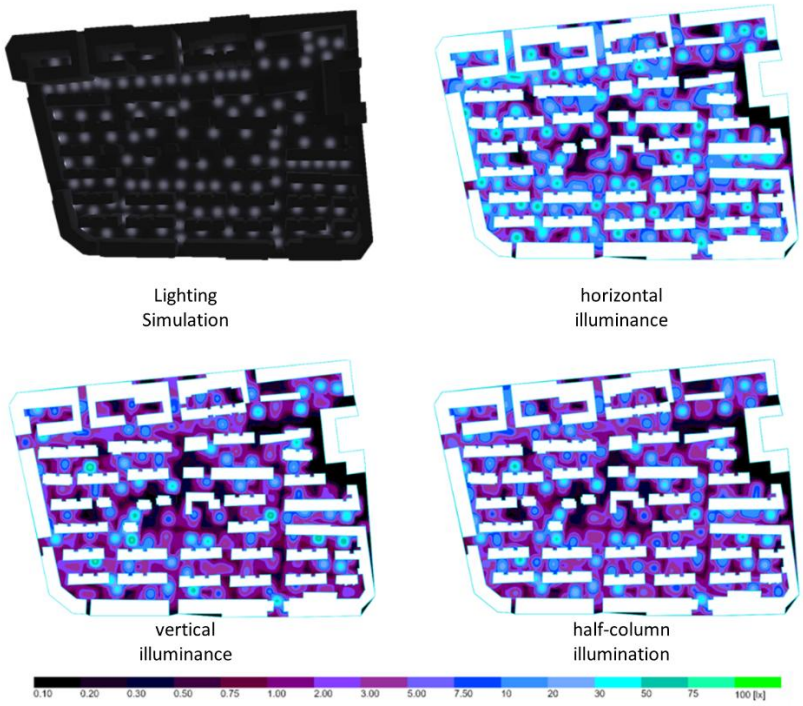


Fig4.7 Optimized simulation results

Comparison of the calculated results of the lighting parameters before and after optimization of settlement I is shown in the table.

Comparison table before and after optimization of settlement I

	Lighting pass rate	Focus region pass rate	Construction cost of lighting fixtures per unit of lighting-eligible area（¥）
pre-optimization	36.7%	11.1%	65
post-optimization	76.0%	60.7%	47

Tab4

As shown in the table, the optimized lighting environment of the residential area has been greatly improved: Firstly, the lighting compliance rate has more than doubled, reaching 76.0%, significantly improving the lighting environment of the residential roads. Secondly, the compliance rate in key areas has increased more than fivefold, reaching 60.7%, significantly enhancing the safety of key areas. Thirdly, the cost of constructing lighting facilities per compliant area has been somewhat reduced. Through the rational optimization of the lighting layout, the utilization rate of lighting resources has significantly increased. It can also be observed that both the overall compliance rate of the residential area and the compliance rate in key areas are still some distance from 100%. This is due to the dual constraints of comfort and cost: excessive lighting facilities require higher costs, and an overly bright nighttime environment is not conducive to residents' rest, compromising their nighttime comfort.

5. Conclusion

5.1 concluding remarks

This paper aims at crime prevention in old residential areas, addressing the poor lighting environment and improper layout planning in old communities in China, and proposes an optimized

lighting layout method for crime prevention. Specifically, based on the expected lighting resource matrix and lighting resource distribution matrix, a lighting layout optimization model is established, and I residential area is used as an example for validation, achieving the purpose of crime prevention. This method not only effectively reduces the occurrence of crimes in old communities, reduces fear and anxiety in nighttime and remote areas, and significantly enhances public safety but also provides a new methodology for crime prevention environmental design. This is achieved by quantifying crime impact factors and environmental design measures and optimizing the lighting layout of residential areas through the establishment and solution of mathematical models to reduce crime. Compared with traditional optimization methods and environmental design, this method has more rigorous design logic and more scientifically controllable design results.

5.2 Shortcomings and prospects

Due to hardware limitations of computers, which result in data biases, in practical design operations, designers still need to further analyze the applicability of computational results. It requires us to adjust different needs of various residential areas based on actual conditions, aiming to achieve crime prevention through optimized lighting layout. In recent years, with breakthroughs in computing power in the field of artificial intelligence, further optimization of computational results and layout schemes through AI is theoretically feasible. Currently, generative design models such as cycle GAN and pix2pix based on neural adversarial networks have been successfully applied in multiple architectural and planning domains. In the foreseeable future, integrating more AI models with traditional design patterns to optimize design workflows has become an undeniable trend. Applying AI technology to validate and expand the models built in this paper, further optimizing the optimization solutions, will make them more practical and significant for guiding practical applications.

When studying the optimization of lighting layouts for crime prevention and their impacts, it is essential to fully consider the diversity of criminal activities and the complexity of residential area typologies, which may introduce certain limitations to the research. The wide variety of crime types means that different criminal behaviors exhibit significant differences in their dependence on lighting conditions. For instance, high-intensity lighting environments may exert a deterrent effect on opportunistic crimes such as street robbery, but their influence mechanisms on premeditated crimes like burglary are more complex. The diversity of residential area configurations further increases research uncertainties. High-rise residential zones, traditional neighborhoods, open-plan communities, and urban-rural fringe areas demonstrate distinct spatial organizations, while residents' activity patterns and safety requirements also differ significantly. Identical lighting layouts may yield divergent security outcomes across varied residential environments, necessitating scenario-specific adjustments to lighting optimization strategies. Additionally, factors such as social governance capacity, surveillance coverage rates, and community security management practices may collectively influence the actual crime prevention efficacy of lighting.

During lighting optimization, a balance must be struck between security enhancement, resident comfort, and energy efficiency. Excessive lighting may cause light pollution, negatively impacting residents' quality of life while increasing energy consumption, whereas insufficient lighting may fail to effectively mitigate crime risks. Therefore, optimizing lighting layouts requires the development of refined intelligent lighting systems that integrate environmental characteristics, resident needs, and social governance considerations to achieve equilibrium between security assurance and sustainability.

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