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Light Pollution Classification and Intervention Based on Assessment Models

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Abstract. With the rapid development of science and technology, landscape and outdoor commercial lighting have become essential but also aggravate light pollution, a new form of environmental pollution. This paper develops a light pollution risk level model and an intervention model. Three regions are selected using the TOPSIS model, considering population, precipitation, GDP, artificial light intensity, and sky brightness. An AHP-based intervention model evaluates cost, accident rate, biological comfort, and persistence. Strategies include reducing light duration and controlling nighttime lighting. For cities like Shanghai, using more glass curtain walls can help, while for sunny cities like Kunming, controlling nighttime lighting is effective. Based on previous studies, this paper compares major cities, obtains customised solutions for different cities, and quantifies light pollution risk level indicators.

Keywords: Light Pollution; AHP; TOPSIS Model.

1. Introduction

With the rapid development of science and technology and the continuous improvement of human living standards, lighting has become an indispensable necessity in People's Daily life. In the city at night, Dazzling lights can be seen everywhere, in the rural streets, the lights of roadside lighting can be seen as well. However, these lights bring us aesthetic pleasure and ease of life, but also bring a huge problem of light pollution. Light pollution is used to describe the excessive or poor use of artificial light. Light pollution is a huge hazard. It affects the environment. It also affects our health. In recent years, light pollution has become a hot topic, among which how to develop light pollution interventions to mitigate these adverse effects, is the core of the problem.

In recent years, many scholars have conducted in-depth studies on light pollution. Zhao Zhihong [1] and others pointed out that the brightness of LED screens in some commercial districts exceeds the standard seriously, in addition, Zhang Junli [2] also pointed out that glass curtain walls can cause urban light pollution, so artificial light is one of the factors affecting light pollution. He Xue'er [3] proposed strategies to mitigate the effects of light pollution such as improving relevant laws and regulations, optimizing urban planning and architectural design, strengthening light pollution monitoring and law enforcement, and adopting intelligent lighting systems to reduce unnecessary night-time lighting. Wang Dongxu [4] et al. used GDP, population size, electricity consumption, adult sleeping hours, brightness level, and wildlife species as indicators of light pollution. Jiang Mengmeng [5], on the other hand, constructed an indicator system for evaluating the risk level of light pollution and proposed an intervention strategy to reduce the risk level of light pollution. Xiong Ruiyu [6] and Wang Zhide [7] made a study on nighttime light pollution. In addition to this, light pollution and other fields are also very relevant. In the field of medicine, Walker [8] and others believe that light pollution and cancer have a certain correlation; Liu Minhui [9] believes that light pollution will have a certain impact on the physiological indicators of newborns, and puts forward corresponding countermeasures. In the industrial field, Qu Yong [10] combined light pollution with pilotage operation in Ningbo harbor and gave countermeasures. It can be seen that light pollution is highly hazardous and everyone should take certain measures to control light pollution.

However, most of today's academic research focuses on a single issue and some regions, and lacks systematic generalization and comparison. By establishing a widely applicable light pollution risk index, this paper compares the pros and cons of intervention strategies, and obtains the best intervention strategies for different regions.

2. Rationale for the assessment model

2.1. Introduction to the TOPSIS entropy weight model

The TOPSIS entropy weight model, as an objective assignment method, is usually applied to problems that require the determination of multiple decision objectives and decision-making of multiple indicators, by calculating the Euclidean distances of different indicators to their positive and negative ideal solutions, and optimizing and ranking them according to the proximity posting progress. The method can fully reflect the gap between the evaluation solutions, achieve the ranking of the advantages and disadvantages of the evaluation objectives and evaluate the relative importance of each examined indicator. In order to assess the light pollution risk level of a specific location, this paper will use the TOPSIS entropy weighting method to analyze five key indicators and calculate their weights, so as to rank the light pollution risk of the selected cities. The specific steps are shown below.

(1) Calculate the original matrix.

(2) Normalize using the original matrix to remove the effects of different index dimensions.

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{1}$$

where z_{ij} is the element obtained from normalization and x_{ij} is the element in the original matrix.

(3) Determine the positive and negative ideal solutions, see formula (2):

$$\begin{cases} z_+ = \max(z_{1+}, z_{2+}, z_{3+}, z_{4+}, z_{5+}) \\ z_- = \max(z_{1-}, z_{2-}, z_{3-}, z_{4-}, z_{5-}) \end{cases} \tag{2}$$

where $\boldsymbol{z}_+$ is the positive ideal solution, indicating the maximum value of the five key indicators in the six cities; $\boldsymbol{z}_-$ is the negative ideal solution, indicating the minimum value of the five key indicators in the six cities.

(4) Calculate the Euclidean distance of the five key indicators to the positive and negative ideal solutions, see equation (3):

The distance between the ith key indicator and the maximum value:

$$D_i^+ = \sqrt{\sum_{i=1}^{5} (z_i^+ - z_{ij})^2} \tag{3}$$

The distance between the ith key indicator and the minimum value:

$$D_i^- = \sqrt{\sum_{i=1}^{5} (z_i^- - z_{ij})^2} \tag{4}$$

(5) Calculate the proximity posting progress. Calculate the proximity of the ith evaluation object to the optimal scheme, using the optimal vector and the worst vector to calculate the proximity posting progress can better compare the rank of light pollution risk in the six cities, as shown in equation (5).

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{5}$$

S_i is ranked from largest to smallest, with larger values of S_i indicating a closer relative distance to the optimal solution.

(6) Standardizing the data.

$$\overline{S_i} = \frac{S_i}{\sum_{i=1}^{6} S_i} \tag{6}$$

(7) Calculation of entropy weight. The formula for information entropy is

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \ (j = 1, 2, ..., m) \tag{7}$$

2.2. Introduction to the AHP model

The AHP (Analytic Hierarchy Process) model, proposed by Thomas L. Saaty in the 1970s, is a multi-criteria decision analysis method suitable for complex decisions involving multiple goals and criteria. It involves hierarchically structuring the problem, subdividing it into key factors, and defining their interdependencies and hierarchical relationships. This creates a structured, multi-level analysis model that clarifies different dimensions and provides a logical framework for decision-making.

(1) Establish a hierarchical structure model. It usually includes a target layer, criteria layer, and solution layer.

(2) Construct a judgment matrix (also known as a pairwise comparison matrix). At the criterion level, pairwise comparisons are made for each criterion, and scores are given based on their relative importance to construct a judgment matrix.

(3) Hierarchical single sorting and its consistency check.

Compute the product of each element of each row of the judgement matrix A to obtain the matrix B.

$$B_i = \prod_{i=1}^{n} a_{ij} \tag{8}$$

$$B = \begin{bmatrix} B_1 \\ ... \\ B_n \end{bmatrix} \tag{9}$$

Calculate the nth root of B_i.

$$\overline{M} = \sqrt[n]{B_1} \tag{10}$$

Obtain the Matrix $\overline{M}$.

$$\overline{M} = \begin{bmatrix} \overline{M_1} \\ ... \\ \overline{M_n} \end{bmatrix} \tag{11}$$

Calculate the weight vector of the ith indicator.

$$M_i = \frac{\overline{M_j}}{\sum_{i=1}^{n} \overline{M_j}} \tag{12}$$

(4) Hierarchical sorting and its consistency check. Combine the weights of the criterion layer and the scheme layer to obtain the relative importance score of each scheme relative to the overall goal.

This article established the AHP model which is shown in Figure 1 by the four steps.

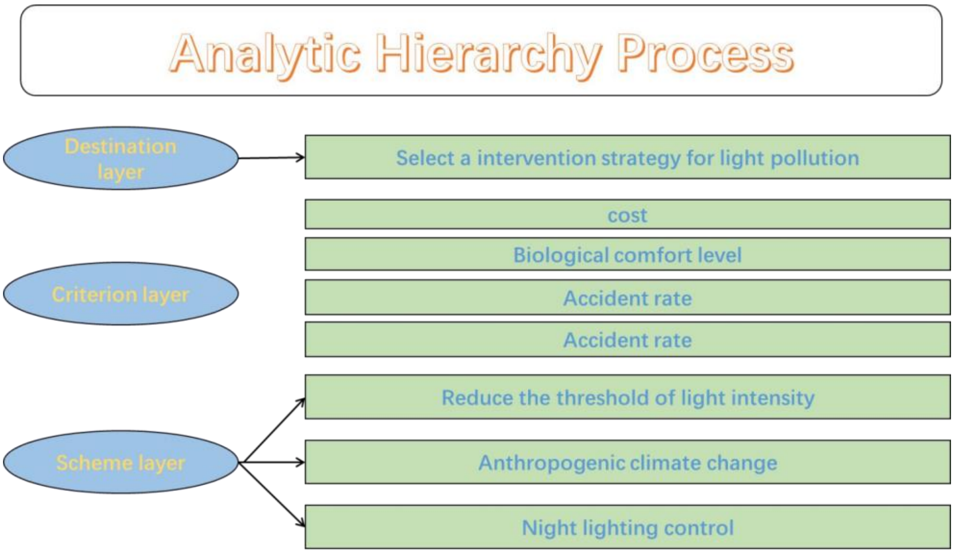

Figure 1. AHP model

3. Results

3.1. The analysis and results of TOPSIS model

First, develop a widely used indicator to determine the level of light pollution risk. Based on the TOPSIS entropy weight model, this article selected Beijing and Shanghai to represent economically developed areas, Wuhan, Dalian, and Kunming as second-tier cities, and Urumqi to represent less developed regions in Northwest China. These cities vary geographically and topographically. After reviewing literature and considering the subject background, this article chose artificial light intensity (L), sky brightness (l), and precipitation (q) as primary evaluation indicators.

The distribution of light spots at night indicates higher light intensity in economically developed and densely populated regions in China due to the prevalence of reflective glass surfaces on tall buildings, contributing to light pollution. This article propose using GDP(k) and population(p) density as indicators for light pollution. To assess the risk level of light pollution in specific locations, this article will use five key indicators. The TOPSIS entropy weight method will be applied to analyze these indicators and calculate their weights, enabling us to rank the light pollution risk for selected cities.

According to the statistical Yearbook of China, this article obtained the corresponding precipitation GDP and population of 6 cities. Through the light pollution map, this article also obtained the artificial light intensity and sky brightness. Based on the above background, utilizing the formula(1), the matrix can be normalized and the final result is shown in Table 1.

Table 1. The normalized matric

	Sky brightness (mcd/m^2)	Artif.bright. ($\mu cd/m^2$)	GDP (100million yuan)	Population (10 thousand)	Annual precipitation (mm)
Dalian	0.2517	0.2455	0.1296	0.1972	0.3865
Beijing	0.5742	0.5781	0.6397	0.5789	0.4683
Shanghai	0.6265	0.6321	0.6874	0.6584	0.2225
Urumqi	0.2766	0.2712	0.0599	0.1077	0.6480
Wuhan	0.3225	0.3185	0.2906	0.3610	0.0785
Kunming	0.1842	0.1759	0.1160	0.2249	0.4023

From Table 1, each index value of the six cities has its own advantages and disadvantages, which is just in line with our expectations. Finally, the score of the standard matric is calculated and normalized. The final normalized matrix is obtained as shown in Table 2.

Table 2. Normalized matrix

Dalian	Beijing	Shanghai	Urumqi	Wuhan	Kunming
0.1080	0.2493	0.2896	0.1048	0.1423	0.1061

Then, calculate the entropy weight. According to the formula(7), the entropy weight corresponding to each index can be got, and then assign the entropy weight to the score matrix to get the final score, as shown in Figure 2.

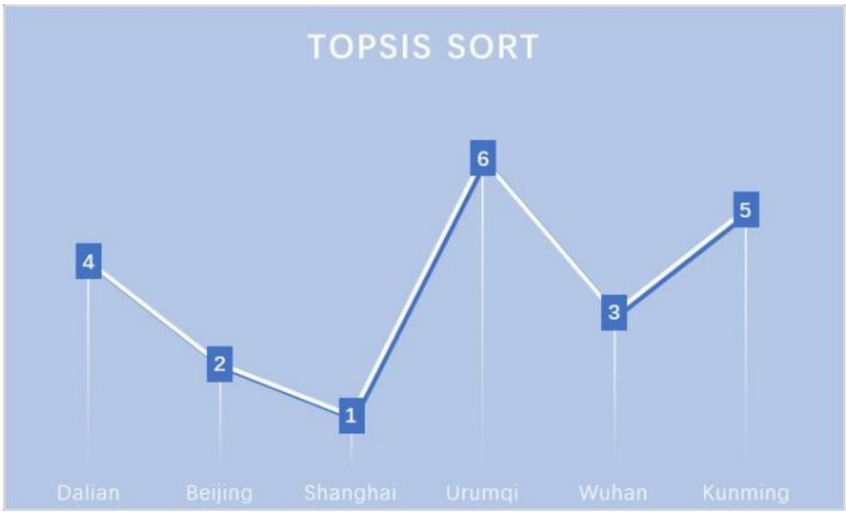

Figure 2. TOPSIS sort

As a result, cities like Shanghai and Beijing, with developed economies and abundant artificial lighting, experience significant light pollution. Kunming, Wuhan, and Dalian, despite economic development, have ample precipitation which thickens cloud cover, reducing light pollution. Dalian, influenced by heavy industry and frequent haze, also experiences lower sky brightness, further limiting light pollution. In desert areas like Urumqi, while light pollution isn't severe, it still occurs, possibly due to isolated developments like solar panels.

Through an illustrative example, this article presents a versatile system for assessing the risk levels associated with light pollution. By reformatting all pertinent indicators to reflect increasing risk as their values rise, we establish a direct proportionality between indicator magnitude and pollution risk. Subsequent normalization of these indicators harmonizes their relationships, enabling us to infer a linear and positive correlation between the risk level of light pollution and the normalized index $(L^{'}, l^{'}, q^{'}, k^{'}, p^{'})$,

$$I = w_1 L^{'} + w_2 l^{'} + w_3 q^{'} + w_4 k^{'} + w_5 p^{'} \tag{13}$$

where w_i is the corresponding entropy weight.

Through the test calculation of several regions, this article speculate that the global light pollution risk level can roughly meet this relationship.

3.2. The analysis and results of AHP model

In this model, this article use analytic hierarchy process (AHP) to analyze the three intervention strategies and their specific measures, and select Shanghai and Kunming to specifically analyze the most effective intervention measures in these two cities.

Combined with the five indicators of the previous model, this article finally established the AHP model, which is shown in Figure 1.

After refining the model, this article use Shanghai and Kunming as examples of urban agglomerations represented by these two cities to provide solutions to maximize the benefits of light pollution interventions.

Through the model, this article score according to the formula

$$M=\sum_{i=1}^{4} w_i x_i \tag{14}$$

where w_i, x_i represent the corresponding weight and indictor.

This article propose three interventions. S1 represents the use of glass curtain walls, S2 represents artificial rainfall, and S3 represents the reduction of street light intensity. Finally, the following score matric is attained in Table 3.

Table 3. Matric of developed cities

	Index weight	S1	S2	S3
Cost	0.1248	0.0974	0.3331	0.5695
Accident rate	0.3056	0.5954	0.2764	0.1283
Biological comfort	0.4918	0.5472	0.1897	0.2631
Persistence	0.0778	0.7692	0.084	0.1468
Score		0.52306648	0.22586838	0.2510957

As can be seen from Table 3, different programmes have different emphases. For developed cities, S1 is rated much higher than S2 and S3, which suggests that developed cities have more money to spend and can pursue other factors more in light pollution intervention. So, we choose S1 in developed cities like Shanghai, that is, increasing the use of glass curtain walls to prevent light pollution.

Then use the same method, and attain the score matric, which is shown in Table 4.

Table 4. Matric for sunny cities

	Index weight	S1	S2	S3
Cost	0.5444	0.0974	0.3331	0.5695
Accident rate	0.1323	0.5954	0.2764	0.1283
Biological comfort	0.0895	0.5472	0.1897	0.2631
Persistence	0.2339	0.7692	0.0840	0.1468
Score		0.3607	0.2545	0.3849

As can be seen in Table 4, for sunny cities, the S3 rating is slightly higher. For these cities, the economy is not as affluent as that of the developed cities, so all aspects need to be considered. As a result, this article choose S3 in sunny cities like Kunming, that is, control light pollution by controlling nighttime lighting.

With the above two models, this article finally determined the light pollution risk level evaluation system. According to the value of I in the light pollution risk level model, the closed interval [0,1] was divided into five equal parts, and ABCDE was assigned five risk level levels from the largest to the smallest. For developed cities, the risk level is relatively high, so S1 can greatly reduce the artificial light intensity, and then reduce the value of I to achieve the effect of reducing the risk level. In sunny areas, S3 reduces the intensity of artificial light while lowering the brightness of the sky, resulting in a significant reduction of I value.

4. Conclusions

In this paper, the light pollution situation in different cities is analyzed and compared by constructing indicators from various aspects, mainly through assessment models, and give specific measures for specific areas while formulating widely applicable light pollution interventions. In the end, this article get the main measures are (1) Choose rough ground glass and other materials in the selection of materials, do not use fully reflective glass. (2) Try not to use glass curtain wall in concave and inclined buildings. (3) Double-layer glass can be installed in the glass curtain wall, and black light-absorbing material can be affixed to the glass on the inside, so as to absorb a large amount of light and avoid the reflection of light. At the same time, supportive measures can be given. (1) When decorating the home, pay attention to minimize the use of too smooth materials, such as the use of LOW radiation of low-E glass, low reflection of glass, reduce the area proportion of glass, etc. (2) More trees will be planted in the city and more green Spaces will be built. (3) Use less or no reflective, heatreflecting building materials in heavy traffic areas. In the residential area, the building materials with no reflection and weak heat resistance are used. (4) For those high-rise buildings under construction, the problem of light pollution will be taken into account in the planning, so as to prevent it before it happens.

Our study provides many feasible suggestions for light pollution intervention, which can help the ecological environment protection. However, our model also has certain shortcomings, such as: (1) The small test sample size makes it difficult to predict globally. (2) The light pollution intervention options which are given are mainly explored based on the five indicators given in the model, in fact, there are more light pollution intervention options. (3) Our model still has some limitations for Northwest China. In future research, climate can also be one of the influencing factors to optimize the model and propose better and more targeted solutions.

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