Embracing Nature: An Optimization Model for Sustainable Tourism Development

Kaixuan Ni

Nanjing University of Posts and Telecommunications, Nanjing, Jiangsu, China

Abstract: Juneau is a small city with a population of only 32,000, close to Canada. Due to the glacial mountains, the only way to get to Juneau from the rest of Alaska is by boat or airplane. The Mendenhall Glacier, located locally, is a well-known attraction and is visited by a large number of tourists during the cruise season, which runs from early April to the end of October each year. However, the growth of the tourism industry has had negative impacts there, such as the receding glacier and a decline in the quality of life for residents. In order to make the tourism industry in Juneau sustainable, we constructed an optimization model to give suggestions for specific measures.

Additionally, we further generalize the model. Among the over-tourism regions, we choose Beijing as the research object. The ecological footprint and sustainable development indicators of the region are considered and measures are proposed to fit Beijing's own situation. Besides, among the regions with few tourists, we choose Qinghai as the target. The data were also processed and analyzed, and the final results show that its tourism industry is declining due to the decrease in the number of tourists. Our suggestion is to promote the natural beauty of the area to attract tourists and thus to see the sustainable development of the tourism industry.

Keywords: Ecological Footprint; Linear Regression; Fuzzy Comprehensive Evaluation; Optimize; Analytic Hierarchy

1. Introduction

1.1 Problem Background

The city of Juneau is located at the foot of Mount Juneau, across the channel from Douglas Island. In terms of area, Juneau is the largest city in the United States, with about 8,430 square kilometers, which is almost the area of the two states of Delaware and Rhode Island combined. Juneau is also the only state capital in the United States with an international border, bordering Canada to the east.

This beautiful seaport city is surrounded by mountains and sea, and can only be reached by plane or boat. And due to its special geographical location as well as historical factors, tourists from all over the world come to visit every year. However, due to the surge in the number of tourists, the local tourist attractions are gradually being destroyed. For example, the Mendenhall Glacier, one of Juneau's main attractions, is continuing to recede due to rising temperatures. In order for Juneau to retain its title as a tourist destination, a sustainable tourism program should be developed[2].

Figure 1. Scenery of the City of Juneau

1.2 Restatement of the Problem

Our mission is to make tourism in the city of Juneau sustainable. Combine economicbenefits with environmental impacts to provide solutions. The specific tasks are as follows：

● Building a model for sustainable tourism in the city of Juneau. Specify optimizations and ,constraints. ,Plan ,and ,clarify ,the ,role ,of , additional ,income ,expenditures. Sensitivity analysis was then performed for the relevant factors.

● Apply the model to areas affected by overtourism and analyze how selected locations change important measures. Examine how the model can be changed in areas with fewer tourists in order to achieve sustainable tourism.

● Write a memo to the Juneau Tourism Commission based on the measures and theresults of the optimization.

1.3 Our Work

To sum up the full article, we

●Evaluation ,models ,were ,established ,for ,ecol ogical ,benefits, ,ecological ,carrying capacity and infrastructure resilience. Then, a fuzzy comprehensive evaluation model of residents' satisfaction was established, and the trend of residents' satisfaction in Juneau in recent years was obtained.

●A dynamic optimization model for tourism based on multiple factors. Combined with the three parameters of sustainable development detection index, resident satisfaction and infrastructure resilience, the ecological benefit was set as the objective function, and the corresponding constraints were obtained. We obtained the optimal number of tourists and the optimal value for ecological efficiency.

●The model is extended to over-touristed and under-touristed cities to optimize the city's sustainability plan by combining local visitor numbers and tourism data in recent years, respectively. Corresponding improvement measures are also proposed.

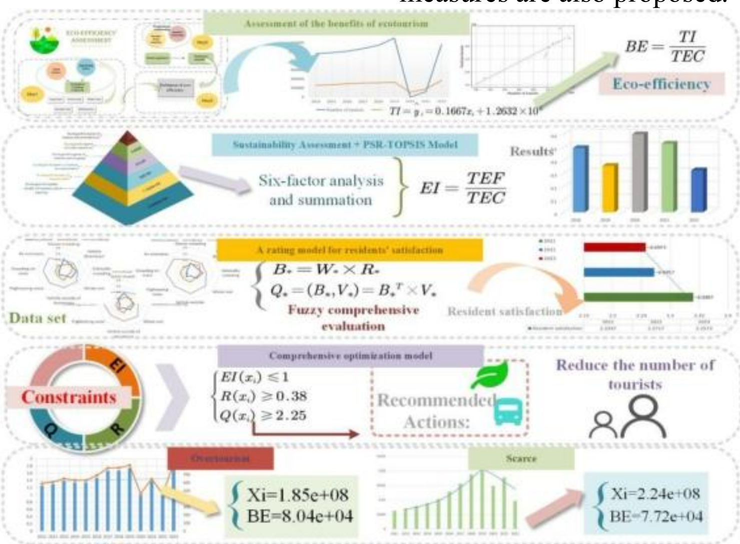


Figure 2. Our work flow

2. Assumptions and Justifications

We make the following assumptions to complete our model through this paper. Furtherimprovements of these simplified assumptions will be achieved later with more reliable data.

●Assumption 1: Tourists' travel activities are not affected by natural factors suchas weather.

Explanation: Most of the modes of transportation chosen by tourists are cruise ships and airplanes, which are less affected by natural factors.

●Assumption 2: The average daily spending of tourists is constant and is not affected by measures such as taxes.

Explanation: Additional revenues such as taxes come mainly from organizations such as steamship companies and are not related to tourists.

●Assumption ,3: ,The ,Residents' ,Satisfaction ,S urvey ,objectively ,reflects ,the attitudes of each resident towards the various aspects of the impact of tourism.

Explanation: In the case of telephone interviews with residents, the unanswered part of the population should be excluded in order to make the results more reasonable.

●Assumption ,4: ,Our ,measures ,have ,been ,properly ,implemented ,and ,have achieved the desired results.

Explanation: For ease of calculation and to reduce the variance of the projections, we determined that the measures were implemented quickly and efficiently.

3. Notations

Table 1. Notations Used in this Paper

Symbols	Definitions
TEF	The tourism ecological footprint
TI	Annual net tourism revenue based on the number of tourists
TEC	Tourism Ecological Carrying Capacity Fuzzy comprehensive evaluation matrix
x_i ,R	Number of tourist
BE	Eco-efficiency

4. Date Collectin

This material does not provide data on the city of Juneau that we will study, so we have collected some important data about this area. Based on our model, we collect data on aspects such as resident satisfaction and population density. Due to the large amount of data, we chose to visualize the data for display rather than listing all the data.

Table 2: Data and Database Website

Database Names	Database Websites
Density	https://juneau.org/
Resident satisfaction	https://juneau.org/wp-content/
Urban data	https://datacommons.org/place/

5. Integrated Sustainable Tourism Optimization Model

5.1 Eco-efficiency evaluation based on tourism ecological carrying capacity and total economic income

Next, we divide into three steps to describe the establishment of an eco-efficiency assessment model.

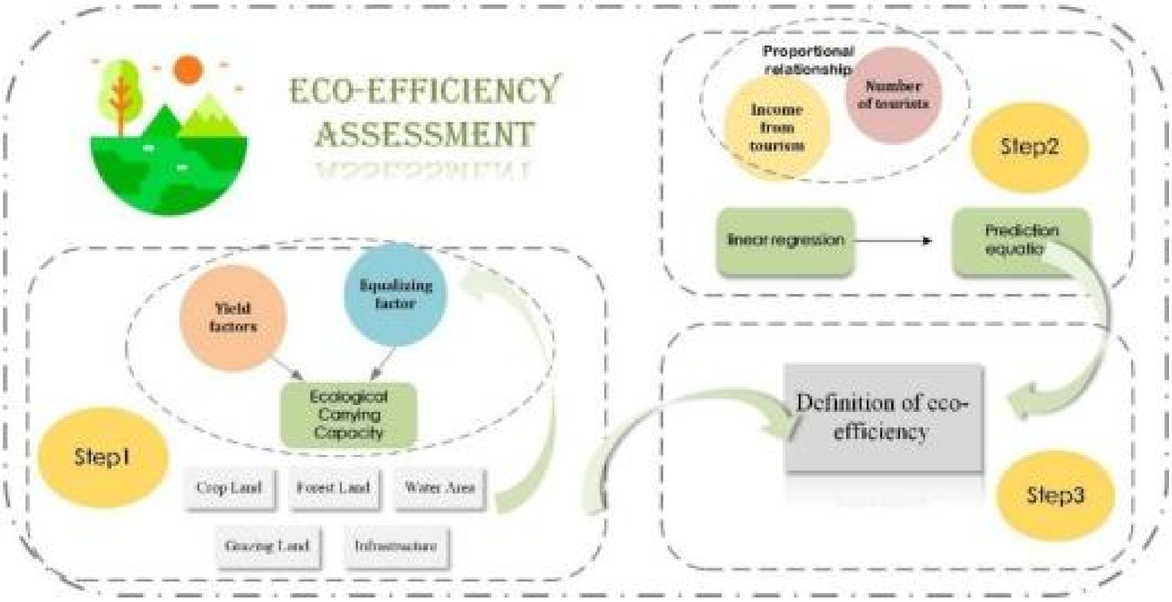


Figure 3. The process of Building an Eco-Efficiency Model

Step 1: Calculation of ecological carrying capacity

Tourism ecological carrying capacity, also known as tourism ecological capacity, refers to the maximum sum of sustainable ecologically productive land area that can be provided to human beings without compromising the productivity and functional integrity of the relevant ecosystems. It is calculated as shown in Equation 1.

$$\mathrm{TEC}=\sum_{i=1}^{n} s_i \times \xi \times \varepsilon_i \tag{1}$$

In this formula, TEC is the carrying capacity of the tourism ecosystem, s_i and ε represents the basic types of land (including forest land, water land, grassland, and built land). Shows the area of Class I land; Indicates the yield factors of the -th land type.represents the equilibrium factor of the -th land type.

Step 2： Linear regression method is used to predict tourism revenue

In order to predict tourism revenue when the number of tourists in the -th year is x_i , taking into account that tourism revenue is proportional to the number of tourists, we use linear regression to build a function between the coordinates of the point and the current revenue value. The linear prediction is shown in Equation 2

$$\hat{y} = ax_i + b \tag{2}$$

The objective function for linear regression minimization is shown in Equation 3

$$J(X_i) = \frac{1}{n}\sum_{i=1}^{n}(\hat{y} - y_i)^2 \tag{3}$$

In the above equation, $J(x_i)$ is the minimized objective function. $\hat{y}$ is the forecast value of tourism revenue in the -th year, and y_i is the true value of tourism revenue in the -th year. We selected the data of tourism revenue and tourist number from 2014 to 2022 for linear regression.

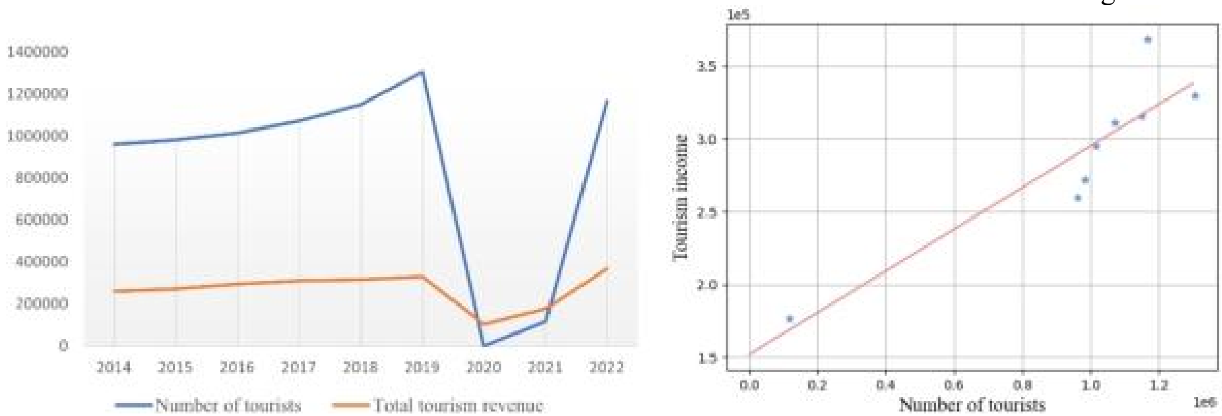


Figure 4. Linear Regression Fits the Data and Results

By minimizing the objective function, the values of the parameters are a=0.1667, b=1.2632*105. Substituting the number of tourists in the -th year is available, and the projected value of tourism revenue in the -th year is shown in Equation 4.

$$TI = \hat{y} = 0.1667x_i + 1.2632\times10^5 \tag{4}$$

After calculation, the variance of this fitting is $R^2 = 0.9074$, and the fitting effect is good.

Step 3: Definition of eco-efficiency

In order to maximize the economic benefits of tourism while reducing the ecological footprint of tourism, we use eco-efficiency as a measure. Eco-efficiency refers to the economic or social benefits achieved per unit of resource consumption or environmental impact[3]. It includes two factors: the ecological footprint of tourism and the economic benefits of tourism, which can be described by Equation 5

$$BE = \frac{TI}{TEC} \tag{5}$$

In the formula, BE refers to the ecological efficiency of a tourist area with a certain number of tourists, and its core is to improve the efficiency of resource use and reduce the negative impact on the environment. And by improving eco-efficiency, we can reduce our ecological footprint while maintaining economic growth, contributing to the achievement of the sustainable development goals of tourism destinations.

Step 4: Data and results

First, we calculated the specific expression of TEF. As shown in Equation 6

$$\mathrm{TEF} = 0.028x + 27.85 \tag{6}$$

When we bring in the number of visitors in 2022, we find that the total annual tourism ecological footprint is $tef = 2.295\times10^4$. The rest of the data is shown in the figure below.As shown in the graph above, we can see that the smallest ecological footprint is occupied by the entertainment aspect. This is followed by the consumption of various scenic spots, which reflects the completeness of the ecological construction of Juneau City. Then there are the shopping and accommodation aspects related to the tourists themselves. Transportation and passenger catering account for the largest ecological footprint. Due to the ,remote location of the city of Juneau cruise ships serve as the main mode of transportation. Therefore, we believe that in the next development and construction, the city of Juneau should focus on road construction. Seafood and other food here are also one of the reasons why Juneau City attracts tourists.

5.2 Sustainability Assessment Based on Tourism's Ecological Footprint and Environmental Carrying Capacity

According to the data, the ecological footprint is defined as the area of ecological land that is converted into natural resources and waste absorbed to meet the needs of a given population within a certain range. The tourism ecological footprint, on the other hand, refers to the level of resource consumption and waste absorption of tourism-related activities within a certain time and space[4]. In practice, it represents the area of ecological land that the tourist needs to accommodate resource consumption and waste absorption during the tour. This indicator is globally standardized, with little regional specificity and direct comparability. Therefore, the tourism ecological footprint can be calculated according to Equation 7

$$TEF = TEFT + TEFE + TEFA + TEFC + TEFS + TEFR \tag{7}$$

The tourism ecological footprint (TEF) can be divided into six categories according to the characteristics of productivity: its calculation mainly includes tourism transportation (TEFT), tourism and tourism (TEFE), tourist accommodation (TEFA), tourism catering (TEFC), tourism shopping (TEFS) and tourism entertainment (TEFR). Below is the definition of each tourism ecological footprint and how it is calculated[5].

●Ecological footprint of tourism traffic

The calculation of theecological footprint of tourism transportation mainly includes two aspects: the area of construction land occupied by tourism transportation facilities and the energy consumption related to tourism activities.

$$\mathrm{TEFT} = \sum_{i=1}^{n}(S_i^F \times \eta_i) + \sum_{j=1}^{m}\left(\frac{\mathrm{N}_j \times d_j \times c_j^t}{\overline{H}}\right) \tag{8}$$

In Equation 2, S_i^F denotes the area of Class I transport facilities. η_i Indicates the utilization rate of category transport facilities. N denotes the number of tourists who chose the j -th mode of transportation. d represents the average distance traveled by tourists who choose the -th mode of transportation. c_i^t represents the per capita energy consumption per unit distance of the -th mode of transportation. $\overline{H}$ represents the average calorific value of the global area of land used for fossil fuel production.

●Ecological footprint of tourist attractions

The calculation of the ecological footprint of tourism mainly includes the construction area of tourist walking trails, roads, and viewing points in each scenic area. At the same time, it also includes the land area converted from fossil energy consumed by the tour vehicles in the scenic area. The energy consumption during sightseeing activities is relatively small, so it is negligible. The specific calculation is as shown in Equation 9

$$\mathrm{TEFE} = \sum_{i=1}^{n}(\mathrm{S}_i^{\mathrm{T}} + \mathrm{S}_i^{\mathrm{R}} + \mathrm{S}_i^{\mathrm{V}}) \tag{9}$$

In the above formula, S_i^T is the built-up land area of the tourist trail in the i -th scenic spot. S_i^R is the area of road construction land in scenic area. The S_i^V represents the built-up land area of the wind landscape attraction in the -th scenic area.

●Ecological footprint of tourism accommodation

The calculation of the ecological footprint of tourist accommodation includes the area of various types of accommodation with beds in hotels, resorts, guesthouses, etc. and the energy consumption required for heating, cooling, lighting, cleaning, television, internet, etc.

$$TEFA = \sum_{i=1}^{n}\left(S_i^B \times n_i + \frac{n_i \times \overline{r_i} \times c_i^b}{H}\right) \tag{10}$$

In Equation 4, n_i denotes the number of beds in a Category I hotel. S_i^B represents the area of land used for the construction of a Category accommodation facility per bed. RI indicates the average annual room rent for accommodation facilities in category. Stands for the energy consumption per bed of a Category accommodation facility.

●Ecological footprint model of tourism and catering

The calculation of the ecological footprint of tourism catering includes the area of built- up land for catering facilities such as catering, banquets, buffets, snacks, and beverages for tourists, as well as the area of ecological land (including arable land, forest land, grassland, and water area) used by tourists for food consumption. It also includes the area of fossil fuel land consumed to provide food and beverage services.

$$TEFC = \sum_{i=1}^{n} S_i^D + \sum_{j=1}^{m} \left(\frac{N_j \times D \times c_j^f}{P_j}\right) + \sum_{k=1}^{w} \left(\frac{N_k \times D \times c_k^e}{H_i}\right) \tag{11}$$

In the above formula, S_i^D denotes the area of built land for various types of socia dining facilities. N denotes the number of tourists. D denotes the average length of stay of tourists, and c_j^f denotes the per capita daily consumption of category food by tourists. P denotes the average productivity of the productive land corresponding to the food in category. c_k^e on the other hand, indicates the per capita daily consumption of Category K energy by tourists.

●Ecological footprint of tourism and shopping

The ecological footprint of tourism and shopping refers to the area of built-up land, biologically ,productive ,land ,and ,fossil ,energy ,land ,in ,the ,production, ,processing, transportation and sales of tourism products purchased by tourists. At the same time, the energy consumption in the production and sale of tourism products is relatively small, and we do not calculate it. The formula for the eco-footprint model of travel and shopping is as follows:

$$TEFS = \sum_{i=1}^{n} S_i^P + \sum_{j=1}^{m} \frac{R_j}{s_i + g_i} \tag{12}$$

Si here indicates the area of land built for the production and sales of the -th tourism product. R is the consumption expenditure of tourists on the purchase of category tourism products. S denotes the average selling price of a tourism product in category. And g represents ,the ,average ,age ,productivity ,of , biologically ,productive ,land corresponding to a single category j tourism product.

●Ecological footprint of tourism and entertainment

The calculation of the ecological footprint of leisure and entertainment only takes into account the area of built-up land and energy consumption of the recreational facilities provided to tourists. It is calculated as Equation 13.

$$TEFR = \sum_{i=1}^{n} S_i^E \tag{13}$$

in Equation 7 is the area of land for the construction of outdoor recreation for tourists in category.

Based on the environmental carrying capacity and ecological footprint of the tourist attraction ,system, ,we ,constructed ,the ,monitor ing ,index EI to ,measure ,the ,green development level of the tourist attraction. As shown in Equation 14

$$EI = \frac{TEF}{TEC} \tag{14}$$

Only when the EI is ,at ,a ,certain ,reasonable value, the tourist ,attraction is ,at ,a sustainable level at the ecological level. By searching for information, we learned that sustainable development is only met when the monitoring indicator meets $EI \leq 1$. We'll describe it in detail below.

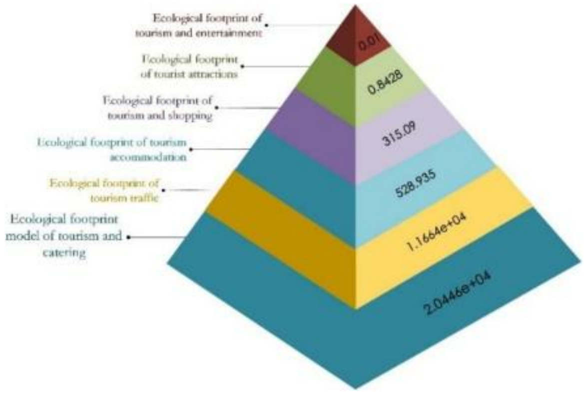


Figure 5. Ecological Footprint Content (hm^2)

5.3 PSR-TOPSIS Infrastructure Resilience Evaluation Model

In order to construct a scientific infrastructure resilience evaluation system, we use quantitative evaluation methods in this section. Firstly, based on the pressure-state-response (PSR) model, an evaluation index system for infrastructure resilience was constructed. Secondly, the entropy-weighted TOPSIS method was used to determine the weights of each index and calculate the resilience level of infrastructure.

Under the framework of the PSR model, infrastructure resilience can be divided into three dimensions: pressure resilience, state resilience and response resilience. According to the specific characteristics of Juneau City, we conducted a data survey on the urban climate, air quality, energy supply and other aspects of

Juneau City. Based on the three resilience dimensions of pressure, state and response, an evaluation index system for infrastructure resilience was constructed.

Then, based on the PSR model, we positivize the negative indicators of the pressure resilience ,dimension. ,Construct ,a ,matrix C associated ,with ,the ,assessment ,area construction by m years and n indicators.

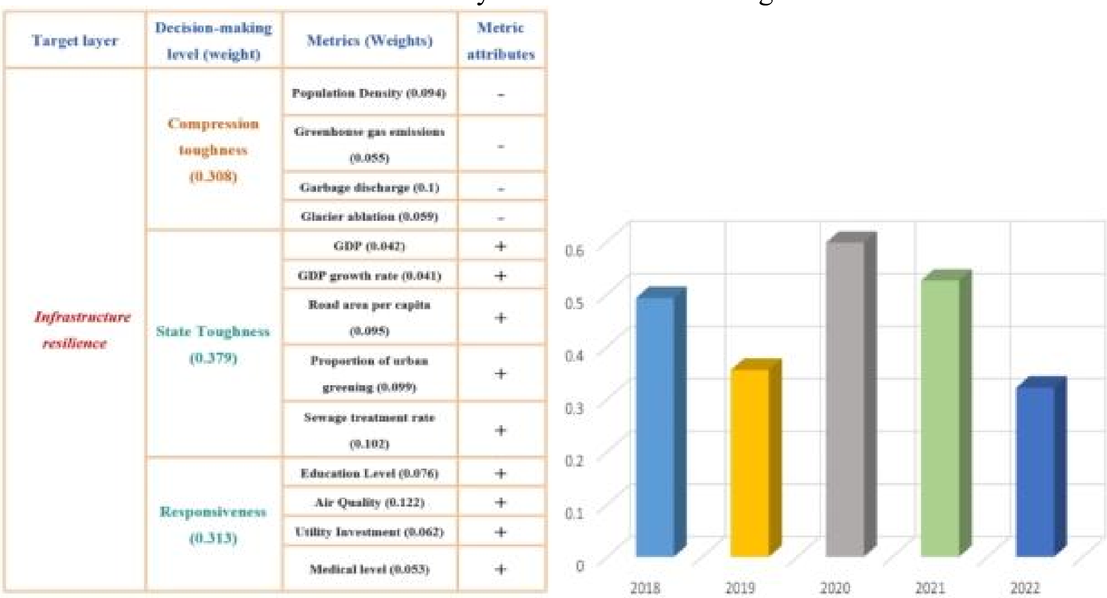
$$C-[c_i]-1,2,3,...,m;-1,2,3...,n \tag{15}$$

In the above equation, c_i denotes the -th indicator of the -th year. The pseudo-code for PSR -TOPSIS is as follows:

Table 1. Pseudo-Code for PSR -TOPSIS

Algorithm 1 PSR-TOPSIS	
Input: Decision matrix: C, Weighting matrix: W, Data normalization method: M	
Output: Juneau's annual infrastructure resilience rankings by composite index	
1: $Z_i \leftarrow \left(C_i - \min\left(C_{i,j}\right)\right) / \left(\max\left(C_{i,j}\right) - \min\left(C_{i,j}\right)\right)$	Standardized decision matrix
2: $Y_{i,j} = \sum Z_i$	Normalization
3: $E_i \leftarrow -1 / \log(m) \sum \left(Y_{i,j} \times \log\left(Y_{i,j}\right)\right)$	Compute criterion entropy Vector of weights for each
4: $W_i \leftarrow \left(1 - S_i\right) / \sum \left(1 - S_i\right)$	indicator
5: $D^+ \leftarrow sqrt\left(\sum \left(W_j \left(Z_i - C_j^+\right)^2\right)\right)$	Forward distance matrix
6: $C_i^- \leftarrow sqrt\left(\sum \left(W_j \left(Z_i - C_i^-\right)^2\right)\right)$	Negative distance matrix Construct relative closeness
7: $R = D^- / \left(D^- + D^+\right)$	

We searched the state of the city's infrastructure from 2018 to 2022 and evaluated each year using the above methodology. The results are shown in the figure below.



Target layer	Decision-making level (weight)	Metrics (Weights)	Metric attributes
Infrastructure resilience	Compression toughness (0.308)	Population Density (0.094)	-
		Greenhouse gas emissions (0.055)	-
		Garbage discharge (0.1)	-
		Glacier ablation (0.059)	-
	State Toughness (0.379)	GDP (0.042)	+
		GDP growth rate (0.041)	+
		Road area per capita (0.095)	+
		Proportion of urban greening (0.099)	+
		Sewage treatment rate (0.102)	+
	Responsiveness (0.313)	Education Level (0.076)	+
		Air Quality (0.122)	+
		Utility Investment (0.062)	+
		Medical level (0.053)	+

Figure 6. Infrastructure Resilience Evaluation Indicators and Results

Based on the mean standard deviation grading method in the information, we classified the level of infrastructure resilience into 3 levels, and determined that the medium level and above satisfy the concept of sustainable development (composite score ≥ ,0.38)[4].

The bar graph data shows that the resilience of the city's infrastructure is decreasing each year due to the rapid growth of tourism and the increase in the number of tourists in Juneau. For this reason, the City of Juneau should allocate a portion of its additional revenue for infrastructure construction and maintenance.

5.4 A Fuzzy Comprehensive Evaluation Model of Residents' Satisfaction

Fuzzy comprehensive evaluation applies the principle of fuzzy relationship synthesis. It consists of factor set, evaluation set, weight set and fuzzy relationship calculation, and is a method of synthesizing the evaluation of the affiliation level status of the evaluated things from multiple factors[7]. Here the fuzzy synthesis evaluation is mostly used together with the hierarchical analysis method.

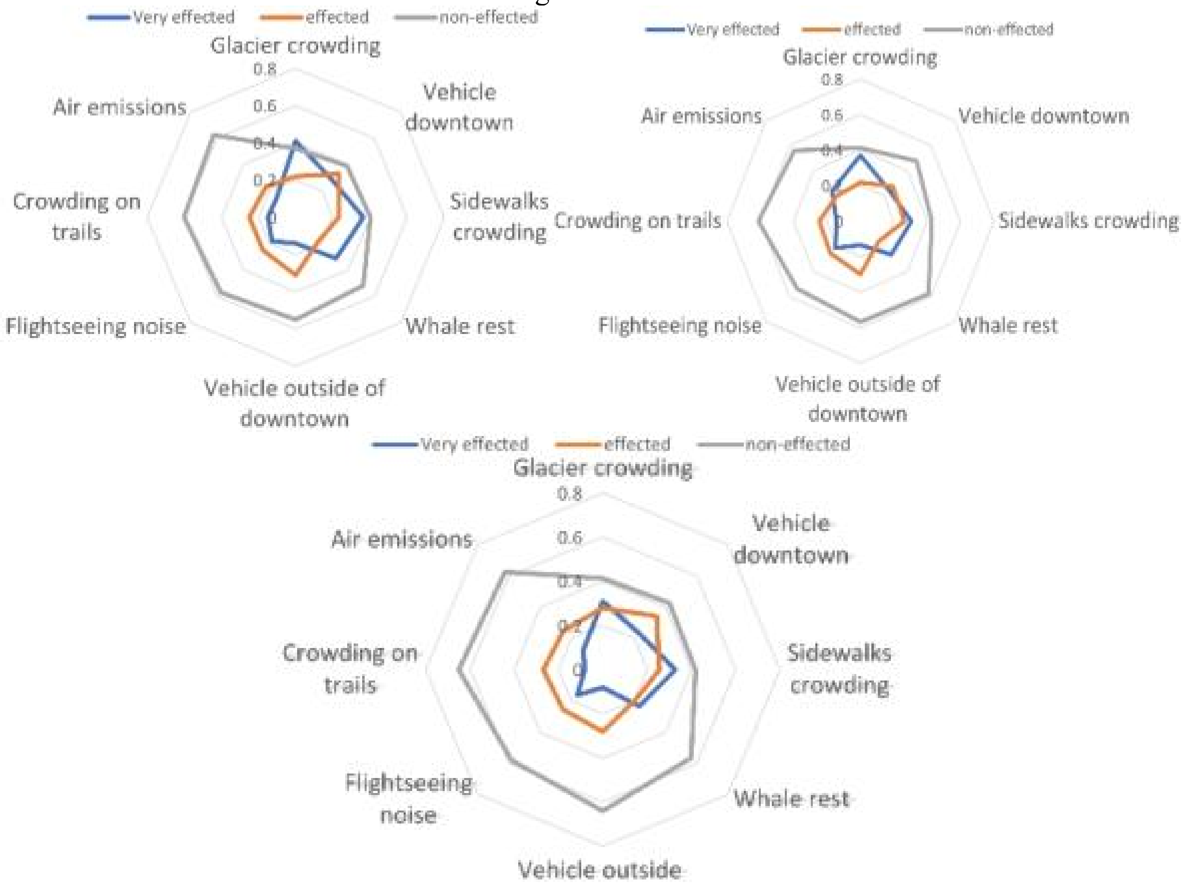


Figure 7. Results of the 2021-2023 Resident Satisfaction Survey

We queried eight satisfaction questionnaires from Juneau residents in recent years regarding congestion on the Mendenhall Glacier, vehicle congestion downtown, downtown sidewalk congestion, whales affected by noise, vehicle congestion outside of downtown, aircraft noise, trail congestion, and air pollutants from cruise ships. The data were also normalized.

Then use the hierarchical analysis method to construct the judgment matrix[8]. The indicators in the index system are compared two by two, and the importance of each indicator is judged. Using the 1 to 9 scale method to evaluate for each two different indicators i and j, the comparative score of i relative to j is obtained. The judgment matrix is thus obtained, and the specific expression is shown in Equation 16.

$$\Phi = \begin{bmatrix} \phi_{11} & \cdots & \phi_{18} \\ \vdots & \ddots & \vdots \\ \phi_{81} & \cdots & \phi_{88} \end{bmatrix} \tag{16}$$

Also available: $\phi = {}^{1}\!/_{\phi}(\neq)$; ϕ=1, $\Phi_1 = (\phi_i)_{4\times4}$,=1,2,3,4 is judgment matrix for social impact. $\Phi_2(\phi_i)_{4\times4} = 5,6,7,8$ is judgment ,matrix of natural influences. By evaluating each other we get a comprehensive judgment matrix.

$$\Phi = \begin{bmatrix} 1 & \frac{1}{2} & 2 & 5 & 6 & 7 & 4 & 3 \\ 2 & 1 & 3 & 6 & 7 & 8 & 5 & 4 \\ \frac{1}{2} & \frac{1}{3} & 1 & 4 & 5 & 6 & 3 & 2 \\ \frac{1}{5} & \frac{1}{6} & \frac{1}{4} & 1 & 2 & 3 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{7} & \frac{1}{5} & \frac{1}{2} & 1 & 2 & \frac{1}{3} & \frac{1}{4} \\ \frac{1}{7} & \frac{1}{8} & \frac{1}{6} & \frac{1}{3} & \frac{1}{2} & 1 & \frac{1}{4} & \frac{1}{5} \\ \frac{1}{4} & \frac{1}{5} & \frac{1}{3} & 2 & 3 & 4 & 1 & \frac{1}{2} \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{2} & 3 & 4 & 5 & 2 & 1 \end{bmatrix} \tag{17}$$

Then use the sum-product method to calculate the judgment matrix. Normalize each column of the judgment matrix first. After normalizing each column, the judgment matrix is summed up by rows. Then normalize the obtained sum vector and calculate the weight of each indicator to obtain the weight matrix $W = [W_1, W_2]^T$. Calculate ,the ,maximum characteristic root of the judgment matrix. Finally, the consistency test of the judgment matrix with the judgment matrix of social impact and the judgment matrix of natural impact is carried out. The formula is shown in Equation 18 (n is 4 in this paper).

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{18}$$

Calculate the stochastic consistency ratio CR .

$$CR = \frac{CI}{RI} \tag{19}$$

Since n is taken as 4, the standardized value of the average random consistency index RI is 0.90.

Then we conducted a fuzzy comprehensive evaluation of the normalized data to comprehensively determine the residents' satisfaction scores in recent years. First, we determine the evaluated object and establish the evaluation factor set: criterion layer factor set $U = \{u_1 \quad u_2\}$, where u_1 is social impact and u_2 is environmental impact. The indicator layer ,factor ,set $u_1 = \{u_{11}, u_{12}, u_{13}, u_{14}\}$, where u_{11} represents ,vehicle ,congestion ,in ,the downtown area, u_{12} represents sidewalk congestion in the downtown area, u_{13} represents vehicle ,congestion ,outside ,the ,downtown ,are a, ,and u_{14} represents ,trail ,congestion. $u_2 = \{u_{21}, u_{22}, u_{23}, u_{24}\}$, where u_{21} represents congestion in the Mendenhall Glacier, u_{22} represents whales awakening from noise, u_{23} represents airplane noise, and u_{24} represents air pollutants from the cruise ship.

Next determine the set of rubrics $V = \{v_1, v_2, v_3\}$. In this paper, the set of rubrics , $V = \{Very \inf luential, non - \inf luential\}$ and ,its ,corresponding ,scale vector ,is $[1,2,3]$ T represents ,the ,score ,obtained. ,Finally, ,the ,fir st-level ,fuzzy comprehensive evaluation is carried out. Using the normalized data to establish the fuzzy comprehensive evaluation relationship matrix R_1 for social impact and R_2 or natural impact. The specific expressions for R_1 and R_2 are shown in Equation 20.

$$R = \begin{bmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & {}_{33} \\ u_{41} & u_{42} & u_{43} \end{bmatrix}, = 1,2 \tag{20}$$

$u_{i,k}$ is the k -th type of evaluation made by the resident on the -th aspect of the -th impact set in the guideline factor. $(i = 1,2,-1,2,3,4; k = 1,2,3)$

The social impact weight vectors W_1 and W_2 obtained by analytic hierarchy process were extracted. Here are the results.

$$\begin{cases} W_1 = [0.289, 0.476, 0.480, 0.059]^T \\ W_2 = [0.125, 0.078, 0.306, 0.492]^T \end{cases} \tag{21}$$

The social impact assessment matrix is $B_1 = W_1 * R_1$, and the natural impact price matrix is $B_2 = W_2 * R_2$

$$\begin{cases} B_1 = [0.293, 0.250, 0.457] \\ B_2 = [0.195, 0.078, 0.306] \end{cases} \tag{22}$$

Then, the comment set was used to assign values to B_1 and B_2 respectively, and the score matrices were set to Q_1 and Q_2 respectively. The specific expression as shown in Equation 23.

$$Q = (B, V_i) = B^T \times V_i (i = 1,2) \tag{23}$$

Finally, the second-level fuzzy comprehensive evaluation was carried out. The specific expression of the second-level fuzzy comprehensive evaluation matrix R_* established according to B_1 and B_2 is shown in Equation 24.

$$R_* = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \end{bmatrix} \tag{24}$$

Continuing to extract the vector of criterion level weights W_* derived from the hierarchical analysis method, the value of the satisfaction rating of the residents of the city of Juneau with tourism development $B_* = W_* * R_*$.

Assigning a value using the set of ratings and setting the score to Q_* , the specific expression for Q_* is shown in Equation 25.

$$Q_* = (B_*, V_*) = B_*^T \times V_* \tag{25}$$

Based on the above conclusions, the evaluation matrix is finally obtained as follows:

$$Q_* = [2.2573, 2.2717, 2.3397] \tag{26}$$

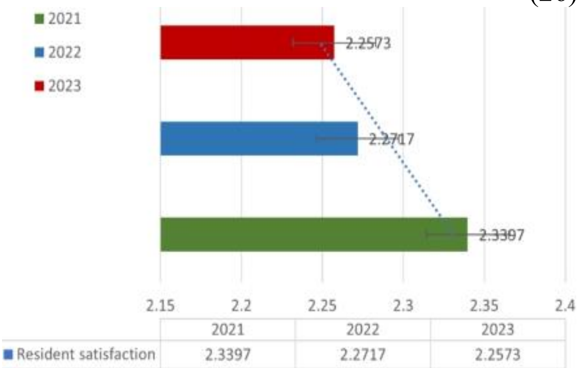


Figure 8. Resident Satisfaction

Rsident satisfaction should be controlled for it to be above 2. Here we choose 2.25 as the lower bound value.

The results show that although the rapid development of tourism in Juneau in recent years has attracted more tourists, it has also directly led to a decline in the satisfaction of local residents. In this regard, we recommend that the relevant authorities take measures to ensure the living conditions of local residents, such as building roads, reducing taxes or adding public facilities.

5.5 A Dynamic Optimization Model for Tourism Based on Multiple Factors

5.5.1 Model building

In this dynamic optimization model, the focus is on five parameters: eco-efficiency, sustainability detection index, resident satisfaction, infrastructure resilience, and infrastructure maintenance costs. These are all functions related to the number of tourists xi, and the definitions and calculations of each parameter are described below.

Eco-efficiency reflects the net tourism benefits or social benefits obtained per unit of resource consumption or environmental impact. After the six-factor TEF model calculation and linear regression of the data can be obtained as $BE(x_i)$.

The sustainability detection indicator EI reflects the degree of overall environmenta impact of tourism in Juneau City, including resource consumption, pollution emissions, and other aspects. After sustainability assessment of tourism ecological footprint and environmental carrying capacity and data fitting can be obtained $EI(x_i)$

The Environmental Carrying Capacity TEC reflects the maximum population size and scale of economic activity that the City of Juneau can support without exceeding the carrying capacity of natural resources and ecosystems. A sustainability assessment of the tourism ecological footprint and environmental carrying capacity and data fitting yields $TEC(x_i)$.

Resident satisfaction Q reflects the overall satisfaction of Juneau residents with the impacts of tourism development and reflects the effectiveness of social management and public policy. After infrastructure resiliency PSR-TOPSIS modeling and data fitting yields $Q(x_i)$

Infrastructure resilience R reflects the resilience and adaptability of the City of Juneau's infrastructure in the face of natural disasters, emergencies, or chronic stress. After a fuzzy composite rating model of resident satisfaction and data fitting yields $R(x_i)$.

5.5.2 Objective function

Setting the objective function to maximize the eco-efficiency e specific expression is shown in Equation 27

$$f(x_i) = -BE(x_i) \tag{27}$$

The negative sign in the formula indicates that it is a maximization problem.

5.5.3 Constraints

The monitoring indicators for sustainable development must meet a certain value in order to ensure the normal development of tourism in Juneau.

$$EI(x_i) \leq EI_{\max} \tag{28}$$

Limit the resilience of infrastructure to allow it to reach the minimum pressure on tourism development. The specific expression is as follows Equation 29.

$$R(x_i) \geq R_{\min} \tag{29}$$

Limiting residents' satisfaction above the corresponding value of normal development is conducive to the sustainable development of tourism. The specific expression is as follows in Equation 30.

$$Q(x_i) \geq Q_{\min} \tag{30}$$

5.5.4 Optimize processes and results

After the integration and calculation of the model, the final results of the constraint factors are as follows.

$$\begin{cases} EI(x_i) \le 1 \\ R(x_i) \ge 0.38 \\ Q(x_i) \ge 2.25 \end{cases} \tag{31}$$

When these constraints are met, the number of tourists is most likely to be 934845. In addition, the optimization results of the final objective function are shown in Equation 32.

$$f(x_i) = -BE(x_i) = -10.686 \tag{32}$$

The optimal result for eco-efficiency was 10.686*103 (dollars per hectare).

5.6 Plan for Additional Income Expenditures

Combining the optimization results with the data queried, we can see that we should reduce the number of tourists by raising taxes and limiting the number of tourists.

Part of the income will be used to improve the ecological environment of the city of Juneau to reduce the impact of tourism on it. A portion of the proceeds will then be invested in infrastructure improvements. The weights of the indicators in Figure 6 show that in practice, air quality improvement should be given top priority, through afforestation or the promotion of public transportation.

These measures will bring the eco-efficiency indicators closer to the optimal value and promote the sustainable development of tourism in the city of Juneau.

6. Expansion of the Model

6.1 Model Application with Over-Touristic Areas

To test the scalability of the model, we try to apply it to over-touristed cities. Taking Beijing as an example which carrying capacity is scaled by urban density, we use the ISTOM model to analyze the local ecological footprint and sustainable development indicators, as shown in Figure 9.

The results in the figure show that the level of sustainable development in Beijing is low. Our optimization results show that the optimal number of tourists in Beijing should be 185 million, and the optimal ecological benefit is 8.04*104 (dollar per hectare). Due to Beijing's special political and economic status, measures such as limiting the number of tourists and increasing taxes are not fully applicable, so we suggest balancing the ecological deficit caused by excessive tourism by improving the compensation system.

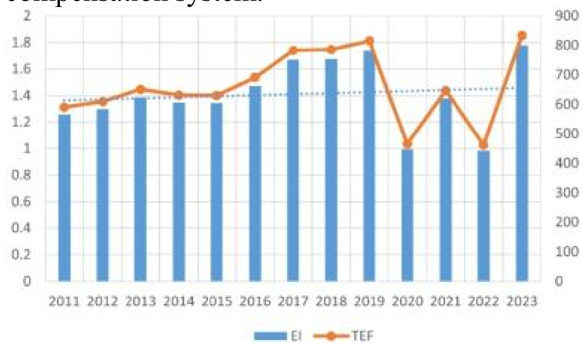


Figure 9. Beijing Tourism Ecological Data of the Past Years

6.2 Model application with sparsely visited areas

In order to further test the scalability of the model, we try to apply it to areas with fewer tourists, and we choose the data related to different land types and ecological footprints in Qinghai Province to simulate the model in part 5 again, and to make a graph of changes in the sustainability indicators of the place over the years as well as a curve of the trend of the changes.

Figure 10. Map of Changes in Qinghai's Sustainability Indicators

Although the graph shows that the level of sustainable tourism development in Qinghai would continue to increase in the absence of measures, due to the small order of magnitude of the EI, this actually reflects the fact that the scarcity of tourists is progressively affecting the development of tourism in Qinghai. In addition, our calculations show that the optimal annual number of tourists in Qinghai is 220 million. The optimal eco-efficiency is 7.72 *104(dollar per hectare). In this regard, we suggest that Qinghai Province should take advantage of its own environmental advantages and vigorously promote its natural scenery. By attracting more tourists to realize the sustainable development of tourism.

7. Sensitivity Analysis

Change the upper limit of sustainable development indicators, the lower limit of urban infrastructure resilience, and the lower limit of residents' satisfaction in the optimization model by 0.05%, 0.1%, 0.15%, 0.2%, 0.25%, and 0.3%, respectively, to observe the changes in the values of the optimization variables and the values of the objective function.

Calculate the corresponding weights after changing the priorities by changing the priorities ,of ,the ,neighboring ,indicators ,in ,the ,judgment ,matrix ,constructed ,by ,the hierarchical analysis determination method in the fuzzy comprehensive evaluation. If the weights do not change much, it means that the temperament scale is not sensitive to the change, and vice versa, it means that the indicator is more sensitive.

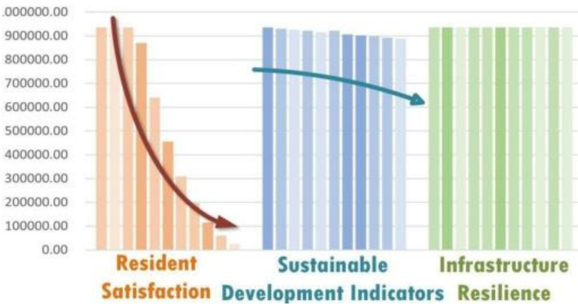


Figure 11. Optimization Results with Different Constraints

Satisfaction's sensitivity reflects direct resident-tourist interactions. As can be seen from the bar chart, increasing resident satisfaction requires a significant increase in the limit on the number of tourists. However sustainability indicators and infrastructure resilience receive almost no impact from the number of tourists. That is this optimization model has low sensitivity to sustainability indicators and infrastructure resilience and high sensitivity to resident satisfaction.

8. Conclusion

The model we developed addresses each point of the problem restatement:

●We first apply the six-factor analysis to calculate the total ecological footprint. Then we predict the net income of tourism and define the ecological benefit as the objective function of the sustainable tourism model. We evaluated the environmental carrying capacity and infrastructure resilience separately. Finally, we integrated the three constraints for optimization to obtain the optimal number of tourists and the optimal eco-efficiency parameters.

●We extend the model to tourist locations that are not used. Beijing was chosen to represent an over-touristed area and Qinghai as a sparsely visited area, respectively. After querying the various tourism-related data of the two, they are brought into the ISTOM model for optimization.

●By extending the model and changing the constraints to perform a sensitivity analysis of the ISTOM model, we conclude that the optimization model has low sensitivity to sustainability indicators and infrastructure resilience, and high sensitivity to resident satisfaction.

References

[1] Yu Hua, Sun Mei. Infrastructure resilience assessment based on PSR model: A case study of Shanghai[J].Building Science and Technology,2024,8(08):5-9.

[2] Sarver J. Case Study: Environmental Impacts of Tourism in Juneau, Alaska[J]. Carolina Planning Journal, 1998, 23(1): 47-53.

[3] Chen Xiaolan, Meng Qinggang, Shi Jianing, et al. Measurement of eco-efficiency
and spatio-temporal evolution analysis of China's eight comprehensive economic zones[J].Economics and Management Review,2022,38(02):109-121.DOI:10.13962/j. cnki.37-1486/f.2022.02.009.

[4] Gössling S, Hansson C B, Hörstmeier O, et al. 2002. Ecological footprint analysis as a tool to assess tourism sustainability. Ecological Economics, 43(2– 3): 199– 211.

[5] Liu Zhongxiu,Nor Kalsum MOHD ISA.Assessment of green development status of mountain-type scenic spots based on tourism ecological footprint model [J].Journal of Resources and Ecology, 2024,15(05): 1324-1334.

[6] Zhou Xinting. Resilience assessment of municipal infrastructure in China based on PSR model[J]. Modern Management, 2025, 15: 1.

[7] Tan Lelin. Fuzzy comprehensive evaluation of residents' satisfaction with tourism development under the background of high-quality tourism: A case study of Dandong City, a frontier tourist destination[J].Journal of Xinzhou Normal University, 2024,40(06):120-126+134.

[8] Yu Shuai. Research on the evaluation of micro-terrain ecological restoration

technology of open-pit mine based on analytic hierarchy process-fuzzy comprehensive model[J].China Mining Journal,2024,33(11):39-48.