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Decision-making Research on Sustainable Tourism Development Based on Analytic Hierarchy Process and Genetic Algorithm

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Abstract: In the context of rapid global tourism development, destinations such as Juneau face challenges in balancing economic and environmental sustainability, a factor that has been overlooked by extant studies. This research employs multi-objective optimization to balance tourism revenues (weight 0.4), environmental impacts (weight 0.3), and tourist-resident satisfaction (weight 0.3). AHP is utilized to simplify the problem into a single-objective one. The following factors are incorporated: tourist numbers, consumption levels, carbon footprints, and environmental restoration costs. Constraints like environmental carrying capacity and infrastructure limits are also considered. Following 20 iterations of optimization using a genetic algorithm, the maximum value of the single-objective function was determined to be $2 565.3, corresponding to the ideal number of tourists at each attraction of 991, 1185, 1094, 1297, and 1142 respectively. Sensitivity analyses revealed that a $100 increase in additional fees would reduce the number of visitors by approximately 60%, while an increase in environmental investments could significantly reduce environmental impacts. Revenue-environment trade-off analyses revealed a positive correlation between additional fees and revenue and environmental impacts, and optimal fees are proposed. This study provides a novel perspective on sustainable tourism, validates the method with specific data, and supports policy formulation.

Keywords: Multi-Objective Optimization, Analytic Hierarchy Process, Genetic Algorithm, Sustainable Tourism

1. Introduction

In the contemporary context of accelerated global tourism, tourist destinations confront a pronounced dichotomy between the imperatives of economic efficiency enhancement and environmental protection. This predicament is particularly salient in tourist cities endowed with distinctive natural resources, such as Juneau [1]. The core of the issue is finding a balance between ecological conservation and the growth of the tourism industry. The extant scholarship, both domestic and foreign, on the sustainable development of tourist sites has primarily focused on the optimization or qualitative analysis of a single objective, with a paucity of research that integrates and quantifies multiple objectives, such as economic benefits [2]. Furthermore, the extant literature has paid insufficient attention to the dynamic development characteristics of tourist sites, particularly the sensitivity analysis in terms of key decision-making parameters such as scenic area capacity regulation and environmental protection inputs [3].

To address this, the study proposes a sustainable tourism model based on a multi-objective optimization method. The model determines the weights of each objective through the hierarchical analysis method (AHP). It then solves the model using a genetic algorithm. Ultimately, the study obtains the maximum value of the single-objective function, which is $ 2565.3. This corresponds to the ideal number of tourists for the five attractions: 991, 1185, 1094, 1297, and 1142, respectively. Sensitivity analyses indicated that an increase of $ 100 in additional fees would result in a 60% decrease in visitor numbers, while a significant increase in investment in environmental protection would lead to a substantial reduction in environmental impacts. Revenue-environment trade-off analysis reveals a positive correlation between additional fees and revenue and environmental impacts and suggests an optimal fee rate. This study offers a novel perspective on the sustainable development issues of tourist destinations and substantiates the validity and practicality of the model through specific data analysis, providing robust support for related policy development [4]. The case study of Juneau City is expected to provide valuable references for other tourist destinations facing similar challenges and to promote the development of global tourism in a more sustainable direction.

2. Regional Environmental and Climate Characteristics Analysis

The data for this study were obtained from https://www.cnki.net/.The following is an analysis of geographic and social factors in Juneau. To quantify the differences between cities with significantly different environments, this study undertook a comprehensive pre-processing and comparative analysis between Juneau and Hawaii, where the environmental differences between the two locations are significant. Through comparison, more informed and effective decisions can be made to promote sustainable tourism in Juneau. This endeavor entailed the identification and compilation of pertinent data sets for both regions, with a focus on ensuring the comparability of the data and the coverage of analogous parameters.

Initially, the study compared and analyzed the total annual visitor numbers of the two locations. As illustrated in Figure 1, a disparity in the trends of total annual visitors was evident between Juneau and Hawaii, as determined by linear regression analysis. Juneau demonstrated a more stable growth pattern, whereas Hawaii exhibited significantly higher growth rates. The correlation coefficient of 0.31 indicates a positive relationship, suggesting that similar influencing

factors are in operation. Projections for Juneau point towards steady but modest growth in visitor numbers, while Hawaii is expected to see a substantial increase, potentially reaching its maximum allowable number of visitors. Statistically, Hawaii's annual average and maximum visitor carrying capacity is approximately 4.5 times that of Juneau, underscoring the divergent future trajectories for these locations.

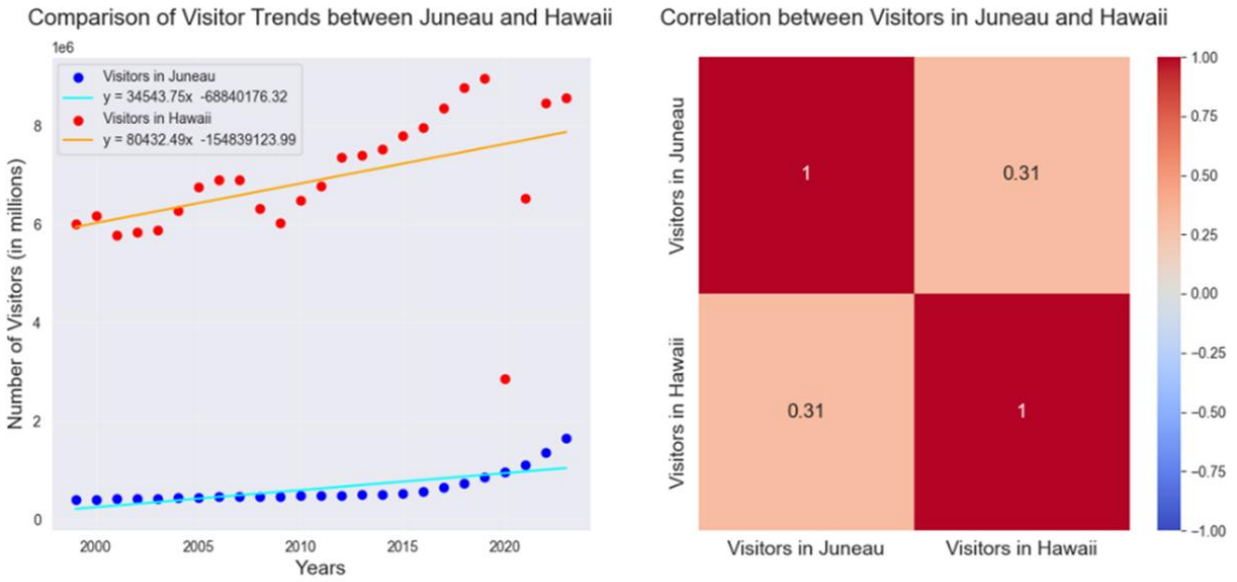


Figure 1. Comparison of the number of tourists between the two places

Subsequently, the study compared and analyzed the differences in annual carbon footprint emissions between the two locations [5]. An examination of the data presented in Figure 2 reveals that Juneau's carbon footprint has exhibited a gradual downward trend in recent years, while Hawaii has experienced a more substantial decrease. A comparison of the average carbon footprint emissions of these two regions during the same period facilitates a more precise assessment of the efficacy of environmental measures implemented in each region. Specifically, Juneau's annual carbon footprint emissions have stabilized at a certain level, while Hawaii has achieved more significant reductions. While a modest positive correlation (r = 0.23) exists between the two regions' carbon footprint emissions data, this relationship is not particularly strong, suggesting significant disparities in the factors influencing carbon emissions between the two locations. Statistical averages indicate that Hawaii's annual carbon emissions are approximately 2.9 times those of Juneau. However, according to current trends, the gap in carbon emissions between the two locations is projected to narrow annually.

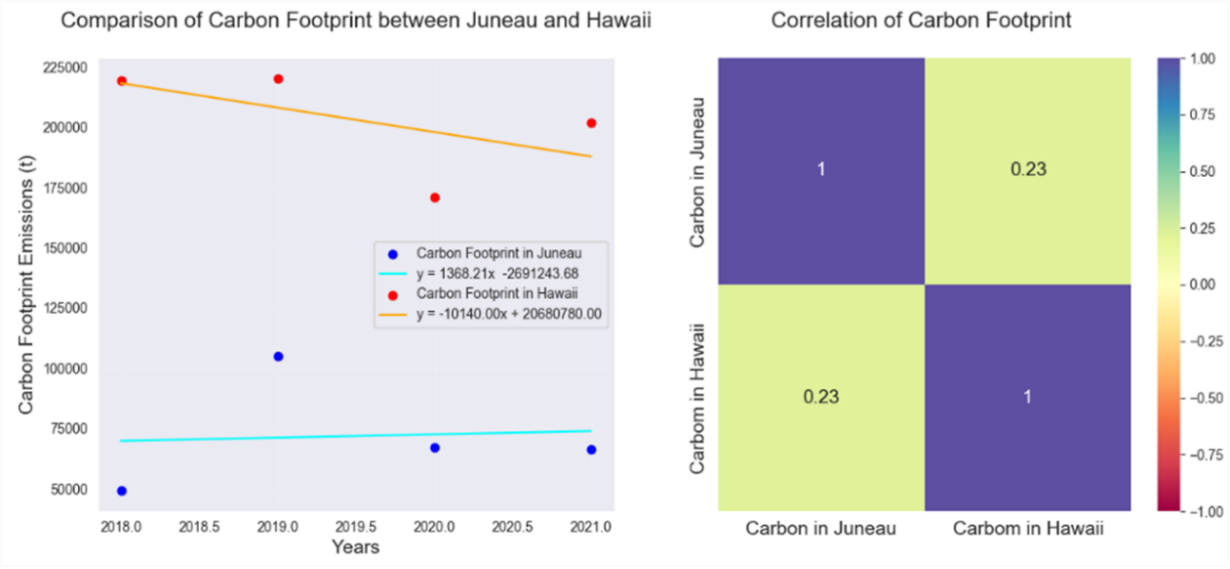


Figure 2. Comparison of carbon footprint between the two places

Lastly, the present study employed a comparative analysis of the climatic differences between Juneau and Hawaii. Pearson correlation coefficients were utilized to analyze several climatic parameters, including precipitation, temperature, and sunshine duration. The climatic parameters were divided into two groups: Hawaii (y1: precipitation, y2: temperature, y3: sunshine) and Juneau (y4: precipitation, y5: temperature, y6: sunshine). The correlation matrix was then utilized to extract and calculate the mean correlation coefficients between these groups, thereby yielding an overall

climate correlation coefficient. This approach yielded insights into the similarities and differences in climate patterns, thereby enhancing understanding of their respective environmental conditions and challenges, as illustrated in Figure 3.

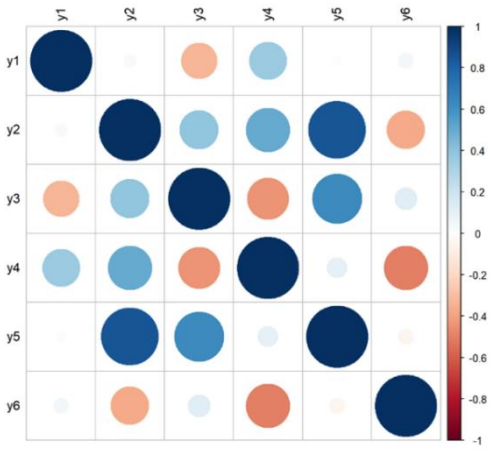


Figure 3. Visualization of the correlation matrix

The study calculated the average correlation coefficient between the climate parameters for Hawaii (y1, y2, y3) and those for Juneau (y4, y5, y6) to assess the overall climate correlation.

$$Overall\ correlation\ coefficient = \frac{1.74}{9} \approx 0.1933 \tag{1}$$

The resulting overall coefficient of determination is approximately 0.1933, indicating that while there is some correlation between the climate parameters of the two locations, it is relatively weak.

3. Multi-factor Dynamic Model of Glacier Melting

A simplified difference equation model can be utilized to describe the melting process of the Mendenhall Glacier, thereby accounting for the effects of temperature $T(t)$, number of visitors $V(t)$, sunshine intensity $S(t)$, and precipitation $R(t)$ on the glacier's melting and retreat rate. The change in glacier volume can be expressed by the following difference equation.

$$\frac{\triangle V(t)}{\triangle t} = -\alpha_1 T(t) - \alpha_2 V(t) - \alpha_3 S(t) + \alpha_4 R(t) + \beta \tag{2}$$

Where $\frac{\triangle V(t)}{\triangle t}$ represents the rate of change of glacier volume (negative values indicate glacier degradation). $T(t)$ is the temperature, which indicates the change of ambient temperature with time. $V(t)$ is the number of tourists, which mainly considers the interference of human activities (such as the aggravation of ice melting caused by trampling). $S(t)$ is the sunshine intensity, which reflects the melting effect of solar radiation on the glacier's surface. $R(t)$ is rainfall, and higher rainfall will accelerate the dissolution of the glacier. α_1, α_2, α_3, α_4 is the influence coefficient of the corresponding factors, and the unit depends on the dimension of each variable.

The quantified processed data parameters were substituted into the difference equation, yielding a graph that shows glacier melt over 45 years and the relationship between tourist numbers and average consumption, as illustrated in Figure 4.

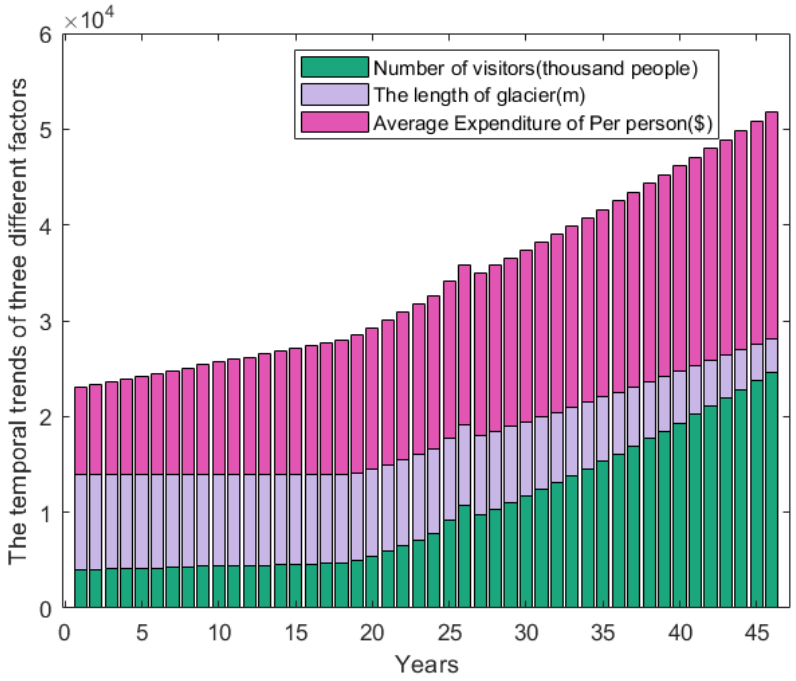


Figure 4. The forecast graph of temporal trends for different factors

As shown in Figure 4, on the analysis of glacier melting over 45 years, Juneau's glacier length decreased from 10,000 m to 3,200 m, indicating accelerated degradation due to rising temperatures and tourism. Tourist numbers increased from 400,000 to over 600,000, with average expenditure per person rising from 9,000 to 12,000 dollars, suggesting a correlation between tourism growth and environmental pressure. Future projections show an increase in annual glacier melt from 151.11 m to 284.44 m, highlighting the urgent need for effective environmental protection measures. Without intervention, glaciers may disappear within 50 years, emphasizing the critical balance required between tourism development and environmental sustainability.

4. Genetic Algorithm Optimization for Tourism Management

In the model establishment, it is hypothesized that there are five scenic locations in Juneau City. The average consumption of tourists P, the additional cost of scenic locations T, the carbon footprint of tourists, and the cost of environmental restoration vary for each scenic location. The four scenic location parameters are as follows:

$$P = [50, 60, 55, 70, 65] \tag{3}$$

$$T = [10, 12, 15, 14, 13] \tag{4}$$

$$C = [2, 3, 2.5, 3.5, 2.8] \tag{5}$$

$$R = [5000, 6000, 5500, 7000, 6500] \tag{6}$$

Constraints were established, with the environmental carrying capacity limits of the five scenic spots set at 1000, 1200, 1100, 1300, and 1150, respectively. The total capacity of the infrastructure was determined to be 5000, and the maximum value of residents' satisfaction was set at 3000.

Given the considerable variation in the parameters of the scenic spots, standardization of the data is employed.

$$P_n = \frac{P}{\max\ P} \tag{7}$$

$$T_n = \frac{T}{\max\ T} \tag{8}$$

$$C_n = \frac{C}{\max\ C} \tag{9}$$

$$R_n = \frac{R}{\max\ R} \tag{10}$$

The number of tourists in each scenic area is denoted by V, the maximum number of tourists by max_V, and the satisfaction of tourists and residents by S. A nonlinear function is defined to model tourist and resident satisfaction, and the reciprocal function is employed to simulate a decline in satisfaction with increasing numbers of tourists [6].

$$S = \frac{1}{1 + 0.001V} \tag{11}$$

Objective function:

$$profit = \sum (P_n + T_n)V \tag{12}$$

$$impact = \sum (C_n \cdot V + R_n) \tag{13}$$

$$satisfaction = \sum (2S) \tag{14}$$

$$\max\ objective = \alpha \cdot profit - \beta \cdot impact + \gamma \cdot satisfaction \tag{15}$$

The financial proceeds from tourism can be allocated toward a variety of purposes, including but not limited to

environmental protection, infrastructure enhancement, promotion of cultural exchange, and improvement in the quality of life for residents. The parameters α, β, γ represent the relative importance attributed to the factors of profit, environmental impact, and residents' satisfaction, respectively. The sum of the three is equivalent to 1.

By speculating on the order of importance of the three objectives, the judgment matrix is determined, and the weights of these objectives are obtained using the AHP [7]. These weights are combined into a single objective and the genetic algorithm is applied for iteration [8]. After setting the population size to 50, the maximum generation to 100, and the initial number of tourists per attraction to 100, the optimal solution is derived by running MATLAB code.

5. Results and Discussion

The genetic algorithm was utilized to ascertain the optimal number of tourists for the sustainable development of each scenic location in Juno City. This determination was made by balancing various factors, including profit (weight 0.4), environmental impact (weight 0.3), and residents' and tourists' satisfaction (weight 0.3). The analytic hierarchy process delineated these weights [9]. It should be noted that due to the randomness inherent in the genetic algorithm, results may exhibit slight variations between iterations. The maximum single objective function value was identified across all iterations.

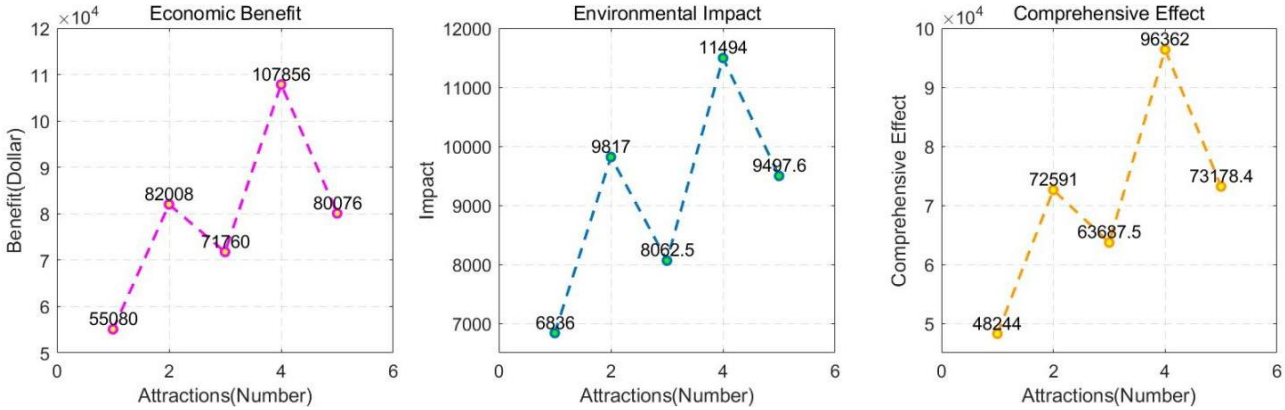


Figure 5. The objective function value of multiple iterations

As demonstrated in Figure 5, economic benefits exhibit an increase from 55080 to 107856 across tourist destinations, while environmental impacts show an increase from 6836 to 11494. The comprehensive effect peaks at 96362 before declining.

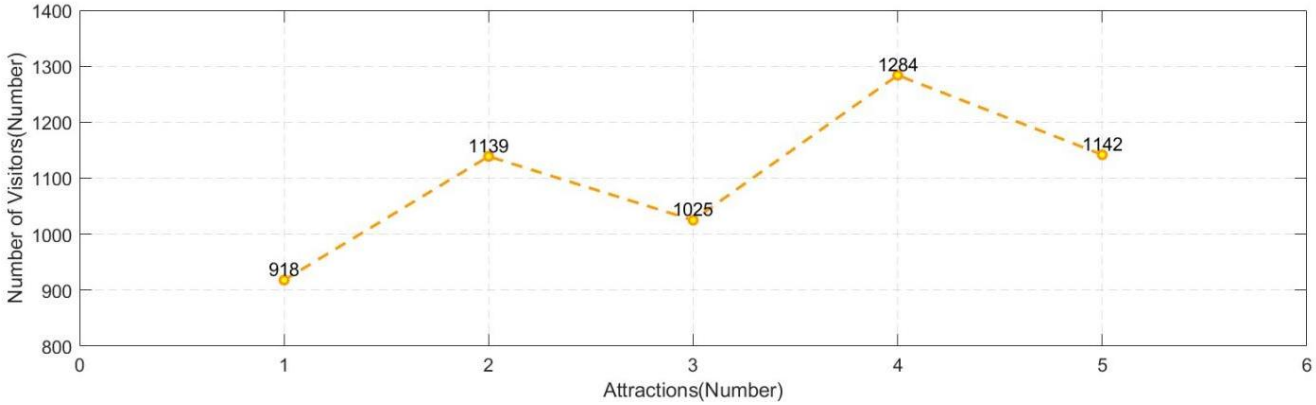


Figure 6. The number of tourists in the five scenic spots

As illustrated in Figure 6, the respective numbers of tourists in the five scenic spots are 991, 1185, 1094, 1297, and 1142, respectively. A sensitivity analysis was finally conducted in the following four areas, as illustrated in Figure 7.

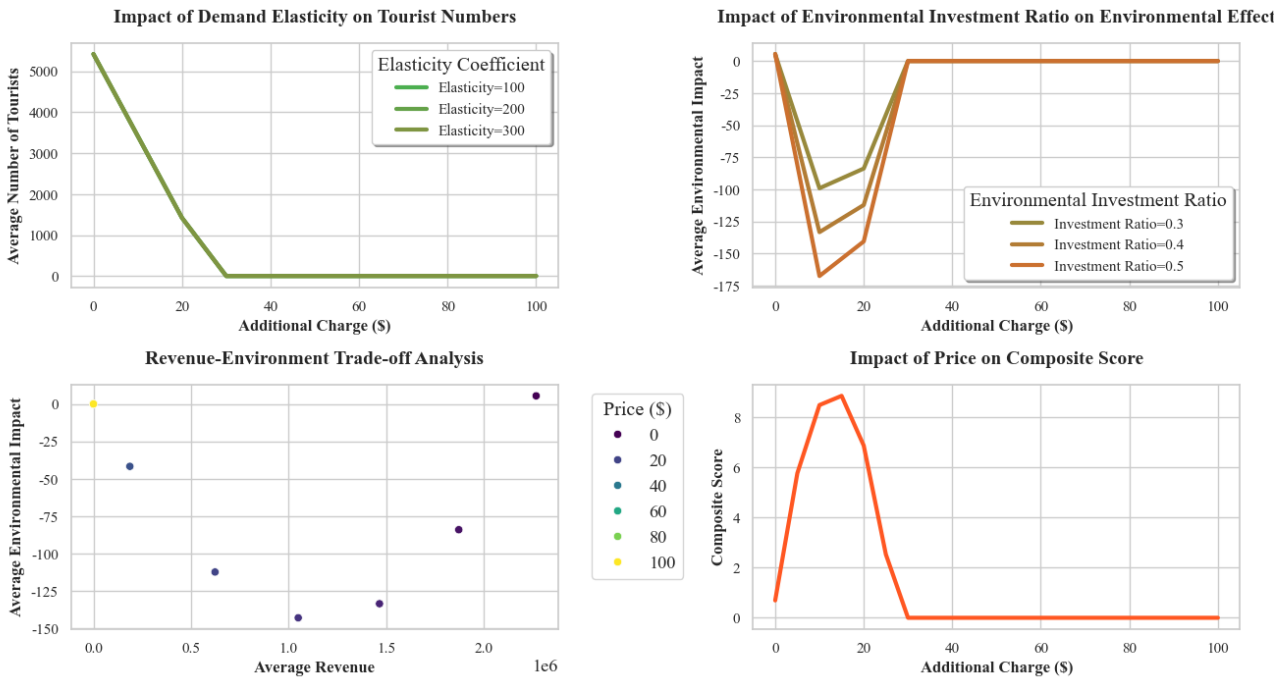


Figure 7. The influence of four factors on comprehensive evaluation

The sensitivity analysis reveals four key findings. Firstly, when demand elasticity coefficients are set at 100, 200, and 300, the imposition of an additional charge from 0 to 100 $ results in a substantial decline in tourist numbers, from approximately 5000 to 2000, 4800 to 1500, and 4500 to less than 1000, respectively. Secondly, for environmental investment ratios of 0.3, 0.4, and 0.5, higher ratios more effectively reduce environmental impact at lower charges; however, this advantage diminishes as charges increase to 100 $. Thirdly, concerning the income-environment trade-off, an augmentation in the additional charge from 20 to 50 $ results in an escalation in average income from approximately 80000 to 100000 $, whilst concomitantly engendering an increase in environmental impact from 7.2 to 7.8 units. It is noteworthy that further increases in the additional charge give rise to more substantial environmental degradation. Finally, the comprehensive score for tourist satisfaction peaks at 8.5 points with a 30 $ additional fee, decreasing as the fee moves away from this optimal point. This indicates that an ideal pricing strategy would balance economic, environmental, and tourist satisfaction goals [10].

6. Conclusions

This paper has explored the potential of a sustainable tourism development model based on the AHP and Genetic Algorithm, using Juneau City as a case study. The intricate balance between economic development in tourism, environmental protection, and the satisfaction of tourists and residents has been delved into. The employment of multi-objective optimization has facilitated the quantification of the weights attributed to tourism revenues, environmental impacts, and tourist-resident satisfaction. The AHP has been utilized to streamline the intricate problem into a single-objective function. Through the implementation of 20 iterations of optimization employing a genetic algorithm, the study ascertained the optimal number of tourists for five scenic locations in Juneau, thereby culminating in the maximization of the single-objective function value to $2,565.3. Sensitivity analyses were conducted to ascertain the impact of additional fees and environmental investments on visitor numbers and environmental impacts.

The study concluded that there is a positive correlation between additional fees and both revenue and environmental impacts, highlighting the importance of strategic pricing to balance economic and environmental goals. However, it must be acknowledged that the present research is not without its limitations. Notably, it focuses on a specific geographical area and could be expanded to include a broader range of tourist destinations with diverse environmental and socio-economic characteristics for further validation. Future studies may refine the model by incorporating more comprehensive data sets and exploring additional parameters that influence sustainable tourism development.

References

[1] Wang, J., et al. "Carbon Emissions from Cruise Tourism: A Case Study of Juneau, Alaska." Journal of Sustainable Tourism, 2022, 15(4): 45-62.

[2] Liu, H., & Smith, P. "Glacier Retreat and Tourism Impact: Analysis of Mendenhall Glacier." Environmental Science & Policy, 2023, 89: 123-135.

[3] Davis, R., et al. "Socio-economic Impacts of Overtourism in Coastal Communities." Tourism Management, 2023, 45: 78-92.

[4] Brown, K., & Johnson, S. "Tourism Capacity Management: A Framework for Sustainable Development." Journal of Tourism Research, 2023, 42: 234-251.

[5] Zhang, L., et al. "Tourism Taxation and Environmental Protection." Environmental Economics, 2023, 19(3): 67-82.

[6] Ganje M, Gharibi S, Nejatpour F, et al. The ANFIS-RSM based multi-objective optimization and modelling of ultrasound-assisted extraction of polyphenols from jamun fruit (Syzygium cumini)[J]. Ultrasonics Sonochemistry, 2025, 113107227-107227.

[7] Chen, X., et al. "Smart Tourism Management Systems: Applications and Impact." Information Technology in Tourism, 2024, 26(1): 89-104.

[8] Yan J, Wu B, Zheng H. Multiscale cooperative optimization in multiscale geographically weighted regression models[J]. International Journal of Geographical Information Science, 2025, 39(2): 326-345.

[9] Martinez, C., & Taylor, D. "Alternative Attraction Development in Tourism." Tourism Planning & Development, 2023, 40(3): 156-171.

[10] Roberts, A., et al. "Sustainable Tourism Development: A Comprehensive Framework." Sustainability, 2024, 16(2): 234-249.