Research on Sustainable Tourism Development Based on Multi-objective Optimization Model and Generalized Linear Regression Model

Dingzheng Yang[1, *, #], Chuhan Bian[2, #]

[1]School of Economics and Finance, Xi’an Jiaotong University, Xi’an, China, 710049

[2]School of Mechatronic Engineering, Xi’an Technological University, Xi’an, China, 710021

*Corresponding author: foreveryang03@163.com

#These authors are contributed equally.

Abstract. The development of tourism can generate considerable income for cities, but at the same time, the chronic overload of tourists puts enormous pressure on the city's waste collection and water supply, incurring high disposal costs. The influx of tourists also disrupts the lives of residents, and the increase in carbon dioxide emissions leads to higher temperatures, resulting in environmental damage. In order to achieve sustainable tourism development，the article built a multi-objective optimization model covering several factors such as the level of the urban environment, tourism profit, residents' living standard, the attractiveness of scenic spots, and the structure of additional government revenue expenditure. By applying the model to Juneau, Alaska, USA, this paper derives the city's optimal tourist carrying capacity in the off-season and peak season of tourism, and through sensitivity analysis, it also derives several important factors affecting the sustainable development of the city's tourism industry, thus providing a reference for the city to realize sustainable tourism development. The model integrates various factors and provides a solution with general applicability for the government to realize the sustainable tourism development of the city.

Keywords: Multi-objective optimization, GLM, Sustainable Tourism.

1. Introduction

Tourism is one of the fastest-growing industries in the world and an important source of foreign exchange and employment. It is closely linked to the social, economic, and environmental well-being of many countries. However, overdeveloped tourism can damage local ecosystems and living environments. Therefore, we need to rationally utilize environmental resources and protect existing resources that have already been developed to sustainably develop tourism based on the triple effect of environment, society, and economy without destroying the local natural environment or damaging existing and potential tourism resources.

In practice, sustainable tourism planning needs to comprehensively consider these different types of carrying capacity and formulate a reasonable tourism development strategy. For example, the carrying capacity of tourist destinations can be improved by limiting the number of tourists, promoting eco-tourism, and strengthening tourism management to achieve sustainable tourism development [1-3]. Relevant studies have been conducted that propose a methodology to maximize the profitability of the tourism-related services sector while taking into account many real-life constraints (e.g., sequentially related travel times, tourist time windows, points of interest, and destination-specific constraints) [4]. The study provided solutions to the problems in the modeling of sustainable local tourism development by using the Metaheuristics algorithm. By conducting sensitivity analysis, the study helps researchers to assess the sustainability and adaptability of tourism business models under different cost and revenue conditions, thus helping decision makers to understand the impacts of different factors on tourism business and develop more flexible and robust business model strategies accordingly.

However, some of the actual factors may have been missed in the relevant studies [5-7]. In this paper, we consider and categorize three major influencing factors: environmental, economic, and social. Based on the summarized factors, we established a multi-objective optimization model [8]. The factors that need to be optimized in the model for the development of tourism are profit and carbon footprint, while the factors that limit the development of tourism are the living standards of residents, the attractiveness of scenic spots, and the structure of government investment and expenditure on its additional revenue for the development of tourism [9-10]. Finally, we applied the model to the Juneau region in Alaska, USA as an example to derive the optimal tourist carrying capacity of Juneau, applied genetic algorithms to analyze the sensitivity of each factor, and obtained the influence intensity ranking of each factor [11].

2. The Multi-objective Optimization Model

The model consists of four parts, as shown in Figure 1.

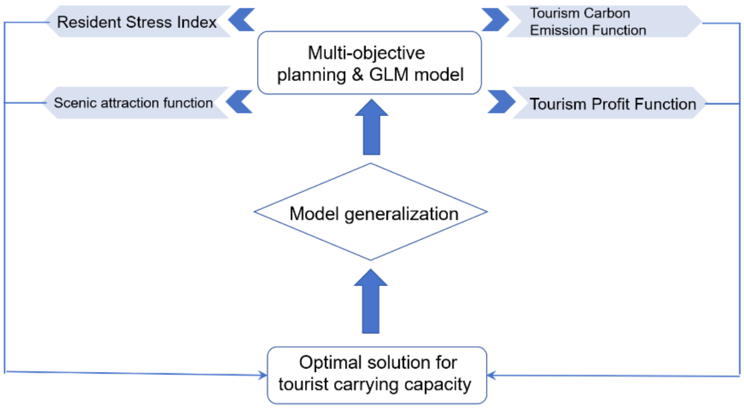

Figure 1. The Multi-objective Optimization Model

2.1. Tourism Profit Function

2.1.1 FCA Analysis Method

Full cost accounting (FCA) is a comprehensive approach to financial management that captures all direct and indirect costs associated with business operations. The specific formula for FCA analysis is as follows.

$$TC = C_d + C_{id} + C_e + C_s \tag{1}$$

where TC is the total cost, C_d is the direct cost, C_{id} is the indirect cost, C_e is the environmental cost, and C_s is the social cost.

2.1.2 Equivalent User Number Theory

The theory of equivalent user number is a quantitative analysis method widely used in cost accounting and resource planning, aiming at solving the complex problem of cost accounting due to the differences in user characteristics and the diversity of needs by constructing a unified measurement standard. The theory takes into account the number of different types of users, their behavioral traits, resource consumption patterns, and related cost factors in a specific system or region, and converts each type of user into an "equivalent user" number with the same resource consumption and cost generation characteristics according to certain rules. The formula for calculating the equivalent user number is as follows.

$$N_e = \frac{N_r}{3} + \varepsilon \times \frac{N}{3} \tag{2}$$

where N_e is the equivalent number of households, N_r is the number of residents, and N is the number of tourists.

2.1.3 Establishment of The Tourism Profit Function

Profit is made up of revenues and costs, and in this model, tourism revenues include spending by tourists, relevant government taxes, and employment income generated through the increase in jobs driven by tourism development. In terms of the cost of tourism development, the cost of waste disposal per capita and the cost of water supply per capita together constitute the cost of development. At the same time, the investment of additional government revenues in infrastructure development leads to a reduction in the cost of tourism development, and this feedback effect is also included in the function. Considering the reality that when the number of equivalent households increases, waste disposal and supply of water will be more difficult, increasing the cost, and the growth effect is consistent with the form of quadratic function. From this, we get the formula for calculating the profit of tourism through integration.

To meet the sustainable development of the tourism industry, we need to maximize the profit of the tourism industry and establish the tourism profit function as follows.

$$max\, P = C_t \cdot N + I_m + T - N_e^2 \cdot (C_r + C_w - \alpha \cdot I_S \cdot T) \tag{3}$$

where P is the profits, C_t is the tourist spending per capita, N is the number of tourists, I_m is the hidden revenue from employment, T is tax revenue, N_e is the equivalent number of households, C_r is the cost of waste disposal per capita, C_w is the cost of water supply per capita, α is the infrastructure development feedback factor, and I_s is the percentage of additional revenue on infrastructure development.

2.2. Tourism Carbon Emission Function

Carbon emissions generated by tourism are categorized as Cruise ship carbon emissions and Carbon emissions per capita. Carbon emissions absorbed are categorized as Carbon sequestration by forests, and Carbon sequestration from environmental inputs.

2.2.1 Carbon emissions from tourism

The formula is as follows, where E represents carbon emissions from tourism, N_e is the equivalent number of households, P_c is carbon emissions per capita, P_0 is carbon emissions per passenger, and N is the number of tourists.

$$E = 3N_e \cdot P_c + P_0 \cdot N \tag{4}$$

2.2.2 Carbon sequestration by forests

Carbon sequestration by forests is linearly related to forest area, and the formula for carbon sequestration by forests is as follows.

$$S_1 = A_f \cdot E_f \tag{5}$$

where E_f is carbon sequestration per square, A_f is the forest area, and S_1 is carbon sequestration by forests.

2.2.3 Carbon sequestration from environmental inputs

According to Climate Change 2007: Synthesis Report, Carbon sequestration from environmental inputs is linearly related to the amount of money spent on environmental investments (e.g., reforestation, and construction of solar energy facilities). In turn, the amount of capital invested in the environment is positively related to Tax revenue, Environmental feedback factor, and Percentage of additional revenue on environmental inputs, where the value is taken to mean the amount of carbon sequestered per dollar invested.

Therefore, the formula for calculating Carbon sequestration from environmental inputs is as follows.

$$S_2 = \beta \cdot I_e \cdot T \tag{6}$$

where S_2 is carbon sequestration from environmental inputs, β is the environmental feedback factor, I_e is the percentage of additional revenue on environmental inputs, and T is tax revenue.

2.2.4 Establishment of Carbon Emission Function for Tourism

Knowing the components of carbon emissions generated and absorbed during tourism, we can derive the formula for net carbon emissions.

To meet the sustainable development of the tourism industry, we need to minimize the net carbon emissions and establish the function of net carbon emissions as follows.

$$min\, E_C = 3N_e \cdot P_C + P_0 \cdot N - A_f \cdot E_f - \beta \cdot I_e \cdot T \tag{7}$$

where E_c is the Carbon Emission, N_e is the equivalent number of households, P_c is carbon emissions per capita, P_0 is carbon emissions per passenger, N is the number of tourists, A_f is the forest area, E_f is carbon sequestration per square, β is the environmental feedback factor, I_e is the percentage of additional revenue on environmental inputs, and T is tax revenue.

2.3. Resident Stress Index

Preliminary analysis shows that the resident stress index is related to the number of tourists and the share of additional government revenue invested in environmental construction. In constructing the functions, we used the GLM fitting model. The generalized Linear Model is a very flexible class of statistical models used to describe the relationship between dependent and independent variables. It is an extension of the linear regression model and can handle different types of dependent variables (e.g. continuous, binary, count, etc.) and different error distributions. The form of the function is shown below.

$$S_r = F(I_s, N) \tag{8}$$

where S_r is the Resident Stress Index, I_s is the percentage of additional revenue on infrastructure development, and N is the number of tourists.

2.4. Scenic Attraction Function

The attractiveness function of the scenic area represents the attractiveness of the tourist area to the tourists, and for the glacier tourist area, we believe that the attractiveness of the scenic area is related to the local air quality as well as the ablation rate of the glacier. It can be expressed as the following equation.

$$S_e = F\left(\Delta V_g, AQI\right) \tag{9}$$

Since the increase in the number of tourists directly leads to a rise in local carbon emissions, the resulting warming will make the glaciers in the scenic area melt, so we believe that the rate of glacier ablation is related to the number of tourists, which can be expressed as the following equation.

$$\Delta V_g = F(N) \tag{10}$$

In addition, local air quality is related to the proportion of additional income invested in environmental protection, which can be expressed as follows.

$$AQI = F(I_e) \tag{11}$$

where S_e is the Environmental Stress Index, ΔV_g is the rate of glacier size reduction, AQI is the Air Quality Index, N is the number of tourists, and I_e is the percentage of additional revenue on environmental inputs.

3. Results

3.1. Solving the Tourism Profit Function and the Tourism Carbon Emission Function

For Juneau, we determined the specific form of Eq. (3) and Eq. (7) through the data where the specific parameters are shown in Table 1.

Since the constant term does not affect the solution, the final equation after removing the constant term is shown below.

$$max\ P(N, I_s) = -1.1 \times 10^{10} \times I_s - 732990 \times N - 0.08592 \times N^2 - \frac{1.1\times10^5 \times N^2 \times I_s}{9} \quad (12)$$

Table.1. Parameters of Juneau & Value

Parameters of Juneau	Value	Parameters of Juneau	Value
C_t	1000	P_0	70
C	1.96×10^9	P_C	5.3×10^4
T	1.1×10^9	A_f	5880
C_r	115.7	E_f	2×10^5
C_w	81.6	β	0.4
α	0.00001		

$$min\ E_c(N, I_e) = 414000000 + 2720 \times N + 440000000 \times I_e \quad (13)$$

3.2. Fitting of the Resident Stress Index

We queried data on the per capita cost of living and per capita annual revenue for Juneau to quantify the resident stress index with the following function and the resident stress index is shown in Figure 2.

$$S_r = \frac{C_l}{I_c} \quad (14)$$

where S_r is the Resident Stress Index, C_l is the Cost of living per capita and I_c is the Revenue per capita.

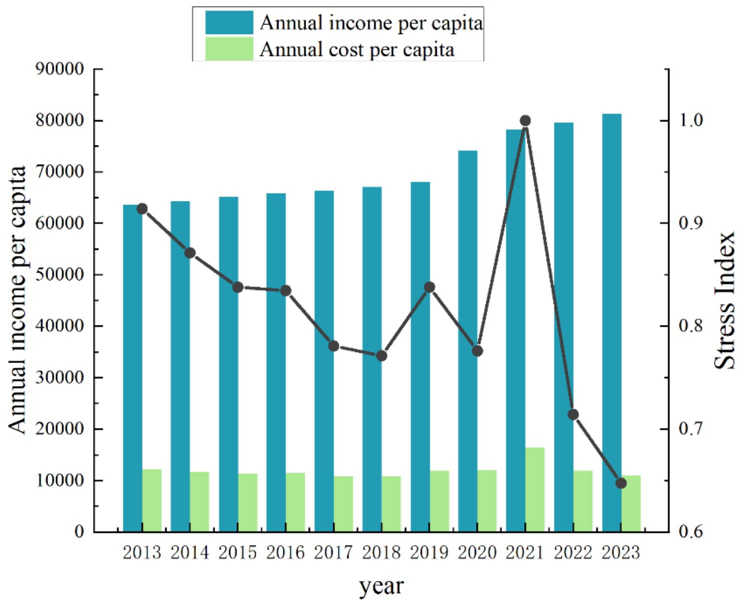

Figure 2. Resident Stress Index

Next, to find the relationship between the resident stress index (similar to Engel's coefficient) and the investment in infrastructure construction and the number of tourists, we used GLM fitting and added a squared term to ensure that the fitted R-squared value is optimal to meet the target requirements. To achieve sustainable development, we refer to the data of resident stress index in previous years and set the limiting value to 0.8, i.e., when the living pressure index is lower than 0.8, it is considered that the residents have a largely supportive attitude towards the development of the tourism industry, and the inequality is as follows.

$$S_r = 0.1411 + \frac{N}{6.9183\times10^6} - 0.2904 \times I_s - \frac{N^2}{9.9972\times10^{12}} + 1.0443 \times I_s^2 \leq 0.8 \tag{15}$$

After fitting, the R2 value is 0.892, which indicates a good fitting result.

3.3. Fitting of Scenic Attractiveness Function

To realize the fitting of the attractiveness function of the scenic spot, we first need to fit the glacier ablation function and the AQI function, and finally substitute them into the Scenic Attractiveness Function. Since AQI has obvious differences in the off-season and peak season of tourism, we will fit the function for the off-season and peak season separately.

Firstly, the fitting of the glacier ablation rate is carried out, according to the scatter plot of the last ten years, we find that the glacier ablation rate and the number of visitors are approximately in a one-time linear relationship, and the fitting result is shown in the following figure with the formula.

$$\Delta v_g = -0.0925 \times N + 1.0443 \tag{16}$$

The scatter plot is shown in Figure 3.

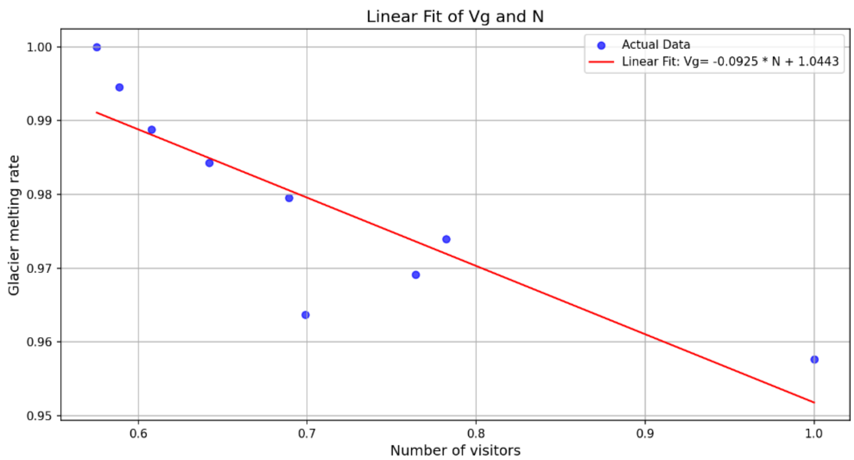

Figure 3. Linear relationship between glacier ablation rate and the number of tourists

Since the data show that the AQI is significantly different between the off and peak seasons (the data are shown in Figure 4), in this part, we fit the AQI separately for the off and peak seasons.

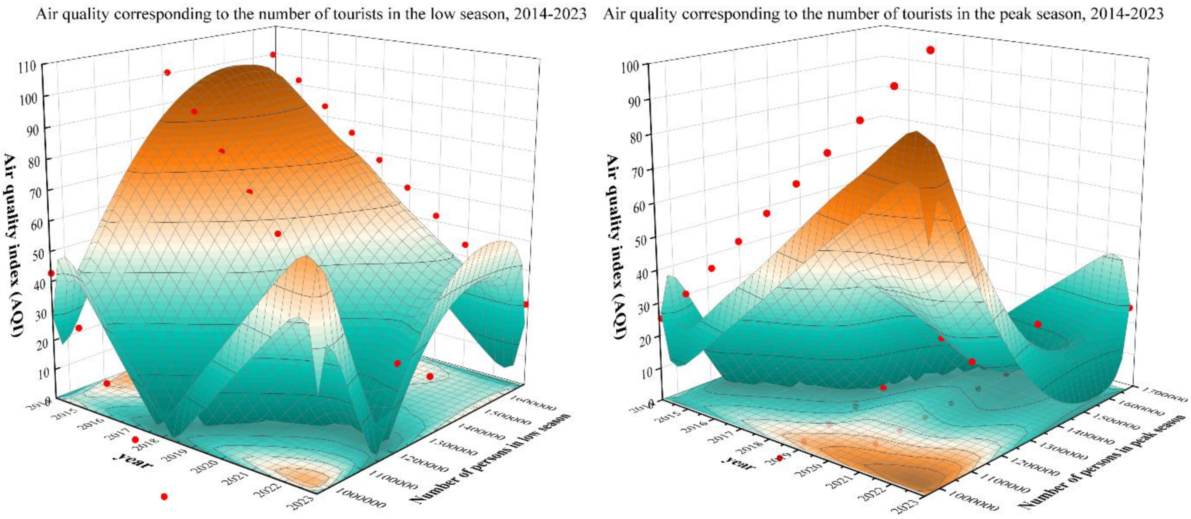

Figure 4. 3D graph of AQI

After analysis, we found that AQI and environmental expenditures approximate a quadratic function during the off-season and an exponential relationship during the peak season. The functions are as follows.

$$AQI_{Low} = 12.0456 \times (T \times I_e)^2 - 22.4521 \times T \times I_e + 11.0714 \quad (17)$$

$$AQI_{Peak} = 0.7680 \times e^{0.0314 \times T \times I_e} \quad (18)$$

To realize sustainable development, it is necessary to ensure that the scenic attractiveness exceeds a certain threshold, according to the data of the past ten years, we set the value of the off-season at 0.75 and the value of the peak season at 0.7, and the inequality for the scenic attractiveness in the off-season and the peak season is as follows.

$$S_{e_{Low}} = 3.1 + 34.5I_e^2 - 5.96I_e^2 + 5.7N \times 10^{-8} \geq 0.75 \quad (19)$$

$$S_{e_{Peak}} = 0.13 + 0.055e^{0.0256I_e} + 4.4N \times 10^{-9} \geq 0.7 \quad (20)$$

3.4. Analysis of the Results

We use the agenetic algorithm to get the optimal solution, for peak season, Eq. (12) with Eq. (13) as the optimization condition and Eq. (16) with Eq. (20) as the constraint. For the off-season, Eq. (12) with Eq. (13) as the optimization condition and Eq. (16) with Eq. (19) as the constraints. In addition to this, the constraints include the following equations:

$$I_e + I_s = 1 \quad (21)$$

After solving the genetic algorithm, we obtained the optimal solutions for the number of tourists visiting N, the proportion of environmental protection input I_e, and the proportion of infrastructure construction input I_s for the off-season and peak season, respectively.

For the off-season, the optimal solution of N is 693000, I_e is 0.38, I_S is 0.62, and the daily carrying capacity of the off-season is 1899 visitors.

For the peak season, the optimal solution of N is 1057000, I_e is 0.71, I_s is 0.29, and the daily capacity of peak season is 2896 visitors.

Table 2 shows the results of the sensitivity analysis for the five parameters C_t, C_r, C_w, α, and T.

Table.2. Sensitivity Analysis of Juneau

parameters	amount of change	ΔN	ΔI_e	ΔI_s
C_t	100.0000	-2×10^6	-0.0500	0.0500
C_r	11.5700	1.5×10^6	0.0400	-0.0400
C_w	8.1600	1×10^6	0.0300	-0.0300
α	0.0000	0	0	0
T	1.1×10^8	-1×10^6	-0.0600	0.0600

After analysis, we ranked the importance of several influences in the model, and the ranking results are as follows (decreasing in importance one at a time from top to bottom):

C_t (Tourist spending per capita)
C_r (Cost of waste disposal per capita)
C_w (Cost of water supply per capita)
T (Tax revenue)
α (Infrastructure development feedback factor)

4. Conclusions and Outlooks

We developed a multi-objective optimization model that took into account the tourism destinations' economic, social, and environmental aspects. The living standards of locals, the allure of picturesque locations, and the structure of government spending are factors that restrict the growth of tourism, whereas profit and carbon emissions are considered optimization factors in the model. By applying this model, it is possible to derive the important factors affecting the development of tourism in a region and the optimal tourist carrying capacity of the region. The model is generalizable to a certain extent and can be applied to different regions by adjusting the specific parameters in the model, providing a reference for sustainable tourism development in various regions of the world.

The model's handling of the attractiveness function of the scenic spots has limitations; only the glacier scenic spots' attractiveness function is provided; in order to construct this function for other areas, new parameters that can represent the scenic spots' attractiveness must be introduced. Further examination of the tourist sector will aid in improving the model, which may have overlooked some other possible elements influencing the growth of sustainable tourism in practice.

References

[1] Moyle B, Moyle C, Ruhanen L, et al. Are we really progressing sustainable tourism research? A bibliometric analysis[J]. Journal of Sustainable Tourism, 2020, 29(1): 106-122.

[2] Kapoor D, Jain A. Sustainable tourism and its future research directions: a bibliometric analysis of twenty-five years of research[J]. Tourism Review, 2024, 79(3): 541-567.

[3] Streimikiene D, Svagzdiene B, Jasinskas E, et al. Sustainable tourism development and competitiveness: The systematic literature review[J]. Sustainable development, 2021, 29(1): 259-271.

[4] Thumrongvut P, Sethanan K, Jamrus T, et al. Metaheuristics in Business Model Development for Local Tourism Sustainability Enhancement[J]. Mathematics, 2022, 10(24): 4750.

[5] Jena S K, Behera C. Mathematical modelling for tourism supply chain considering sustainable effort[J]. INFOR: Information Systems and Operational Research, 2022, 60(1): 20-51.

[6] Bertocchi D, Camatti N, Giove S, et al. Venice and overtourism: Simulating sustainable development scenarios through a tourism carrying capacity model[J]. Sustainability, 2020, 12(2): 512.

[7] Darvishmotevali M, Rasoolimanesh S M, Dorbeiki M. Community-based model of tourism development in a biosphere reserve context[J]. Tourism Review, 2024, 79(3): 525-540.

[8] Higgins A J, Hajkowicz S, Bui E. A multi-objective model for environmental investment decision making[J]. Computers & operations research, 2008, 35(1): 253-266.

[9] Sattraburut T, Prueksakorn K, Kitcharoen T, et al. The Connection between Phuket’s Water Supply and the Hotel Sector’s Water Use for Assessment of Tourism Carrying Capacity[J]. Sustainability, 2024, 16(2): 621.

[10] Xu X, Feng C, Zhen D, et al. Evaluation of the environmental costs of tourism based on an emergy analysis of tourism waste disposal: a case study of Yarlung Zangbo Grand Canyon National Park in Motuo County, Tibet[J]. Environmental Science and Pollution Research, 2021, 28: 32708-32720.

[11] Haupt S E, Haupt R L. Genetic algorithms and their applications in environmental sciences[J]. Advanced Methods for Decision Making and Risk Management in Sustainability Science; Nova Science Publishers: Hauppauge, NY, USA, 2007: 183-196.