Problem Chosen	2025 MCM/ICM Summary Sheet	Team Control Number
B		2506398

Tourism in Flux: Multi-Objective Optimization for Sustainable Development in Juneau

This paper focuses on the **sustainable development of the tourism industry** in Juno, Alaska, and proposes a multi-objective optimization model to balance tourism revenue, environmental impact, and resident well-being. Optimize tourist management strategies through **multi-objective particle swarm optimization (MOPSO)** algorithm and dynamically adjust them in combination with feedback mechanism to improve the sustainability of the tourism industry.

In Model I, we combine multiple factors such as tourist numbers, average consumption, carbon emissions, and resource consumption into a unified multi-objective optimization framework, and use **principal component analysis (PCA)** to reduce the dimensionality of complex tourism, environmental, and economic data. Through PCA method, we extract key variables from a large amount of raw data to reduce the dimensionality of the data and preserve the most influential information. Then, the MOPSO algorithm is used to optimize these reduced dimensional data and solve for the optimal tourist management strategy, maximizing tourism revenue while ensuring minimal environmental impact and resident burden. In addition, in order to further optimize residents' well-being, the model introduces a **feedback mechanism** for additional income expenditure plans, aimed at returning some tourism revenue to local residents and ensuring that they can fairly share the economic benefits brought by the tourism industry. Through sensitivity analysis, we evaluated the effectiveness of various measures and optimized corresponding intervention strategies.

In Model II, we introduced **evolutionary game theory** based on Model I to analyze the game relationship between the government, tourism industry, and residents. The goal of this model is to find the optimal resource allocation plan between the government and the tourism industry to achieve a balance of interests, and to determine the most effective policy intervention measures through the results of evolutionary game theory. This model is not only applicable to the city of Juno, but also demonstrates how to balance the sustainable development of the tourism industry in a famous tourist city like Venice by combining it with the case of Venice. By integrating the new model, we can analyze the results of various interest games based on the specific situation in Venice, optimize tourism policies, solve the problem of excessive tourism, protect the environment, and improve residents' well-being.

The optimization model proposed in this study can provide systematic decision support for tourist cities like Juno, which not only helps to improve the economic benefits of the tourism industry, but also effectively reduces the negative impact on the environment and ensures the improvement of residents' quality of life. Through data-driven strategies and flexible intervention mechanisms, this model provides valuable reference and practical guidance for sustainable tourism development in similar regions.

Keywords: Sustainable Tourism; Multi-Objective Optimization; MOPSO; Game Theory

Contents

1 Introduction

1.1 Problem Background

As global tourism rapidly grows, cities like Juneau, Alaska, face increasing pressures from environmental, social, and economic factors. Despite its attractive tourist destinations, Juneau saw over 1.6 million cruise ship visitors in 2023, leading to overcrowding, infrastructure strain, and environmental challenges. The Mendenhall Glacier, a key attraction, has been receding due to climate change and overdevelopment. Local residents worry that the glacier's disappearance will harm the city's tourism industry.

With hidden costs such as infrastructure pressure, waste management issues, and a larger carbon footprint, sustainable development in Juneau has become a major challenge. The city has introduced measures like higher taxes and tourist limits, but these have sparked controversy. Some residents fear that higher fees could reduce tourism revenue, while others call for stricter controls to ease local pressures.

In this context, finding a sustainable tourism model is crucial. Our research focuses on multi-objective optimization, assessing factors like tourist numbers, environmental needs, and economic pressures. We will also apply game theory to analyze stakeholder interests and support the development of effective sustainable tourism strategies. This study aims to provide solutions for Juneau and similar cities to balance ecological preservation with economic growth sustainably.

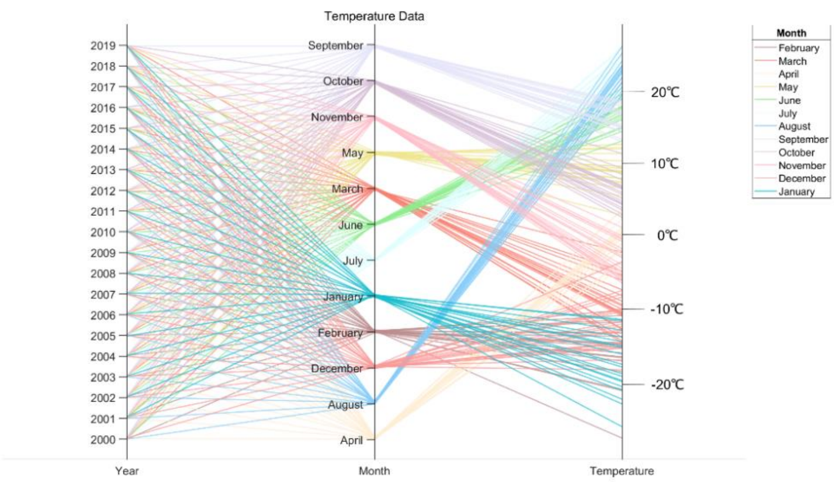

Figure 1: City of Juneau Temperature Change Chart

1.2 Restatement of the Problem

Considering the background information and restricted conditions identified in the problem statement, we need to solve the following problems:

- Problem 1 requires us to build a model describing sustainable tourism applied to the city of Juneau, Alaska, and consider both internal and external factors. Based on the model and the factors considered, determine the optimization objective as well as the constraints. A spending plan for additional revenues was outlined to show how these expenditures would feed back into the model of sustainable tourism. Finally, a sensitivity analysis of each factor is conducted to make a judgment on the importance of each factor.

- Problem 2 requires us to confirm the generalizability of the model's transferability to other destinations similarly affected by over-tourism. And to explain which measures are most important for the chosen locations and how the modeling can be used to promote the development of less visited locations to achieve a better balance.
- Problem 3 requires us to write a one-page memo covering our projections, the effects of each measure, and recommendations for improving the results for the City of Juneau Tourism Commission.

1.3 Literature Review

The tourism industry faces significant challenges, such as climate change, resource scarcity, social equity, and economic imbalance. Optimizing tourism decisions to foster long-term sustainable development has become a focus for both academics and policymakers. With advancements in big data and AI, the feasibility of developing sustainable tourism models has increased. These models play a crucial role in balancing environmental, social, and economic impacts while ensuring the industry’s growth and stability.

Several studies have made notable contributions to this field. Roberta Arbolino introduced a multi-objective optimization model to help public administrations allocate resources efficiently, considering environmental, social, and economic factors[1]. Yedidya Levi applied a bilevel optimization model to artificial island planning, using genetic algorithms to optimize land use and transport networks[2]. Mónica García-Melón developed an evaluation method promoting stakeholder participation in national park management through the Analytic Network Process (ANP) and Delphi judgment procedures[3]. Baozhuang Niu's research on Build-Operate-Transfer (BOT) contracts explored the impact of demand uncertainty on tolls, road capacity, and concession terms, enhancing contract efficiency[4]. Alexandra V. Michailidou proposed a climate change mitigation and adaptation framework using Multi-Criteria Decision Analysis (MCDA), prioritizing energy and water management in Greek tourism[5].

Despite progress, existing research faces challenges, including the lack of comprehensive models addressing complex global socio-economic and environmental factors, limited practical applicability, and variations in stakeholder participation. Additionally, research on uncertainty and risk management remains insufficient, particularly regarding dynamic changes and external shocks.

Our work addresses these gaps by employing Principal Component Analysis (PCA) to reduce the dimensionality of tourism factors, focusing on key elements that impact sustainability. We then used a multi-objective optimization model to identify Pareto optimal solutions, applying the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm for efficient computation. Furthermore, we incorporated Multi-Agent Reinforcement Learning (MARL) to model the interactions between governments and local communities, facilitating a balanced and sustainable solution.

This approach offers an improved, comprehensive solution by combining data reduction, multi-objective optimization, MOPSO, and MARL, enhancing computational efficiency and providing valuable support for sustainable tourism decision-making.

1.4 Our Work

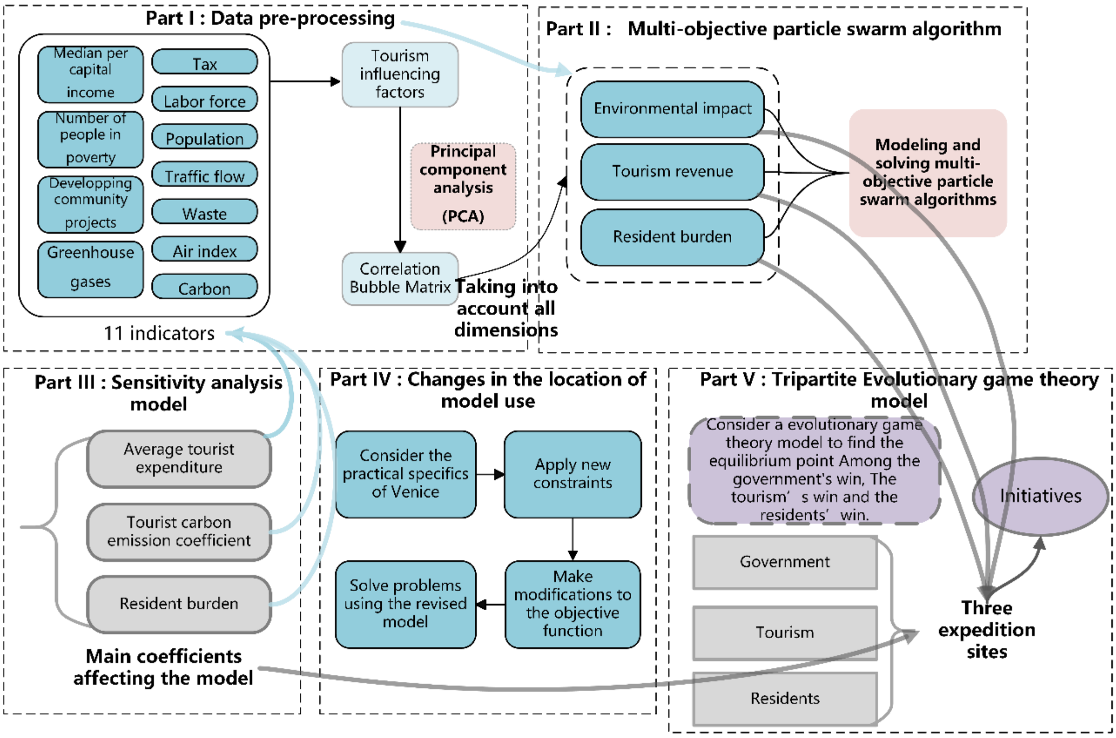

Figure 2: Flow chart

2 Assumptions and Justifications

- **Assumption 1**: Economic income is simplified as the product of the number of tourists and average consumption, ignoring other factors that might influence tourism revenue, such as seasonality and differences in the consumption behavior of different tourist groups.
  Justification: This assumption simplifies the calculation of economic income by avoiding complex factors. While tourism revenue is influenced by various elements, such as seasonal fluctuations and different tourist groups' spending habits, this simplified model ensures calculation feasibility while revealing the basic relationship between revenue and key variables.
- **Assumption 2**: Environmental impact is measured solely by carbon emissions and resource consumption, with the assumption that these factors have a linear relationship with tourist numbers.
  Justification: To reduce complexity, the model focuses on two main factors: carbon emissions and resource consumption, assuming a linear link with tourist numbers. While environmental impact is influenced by various complex, non-linear factors in reality, this assumption provides a manageable starting point and offers useful guidance for decision-making.

- **Assumption 3**: The development of the tourism industry is not influenced by extreme disasters, epidemics, or other sudden events.
  Justification: To simplify external uncertainties, this assumption excludes low-probability, unpredictable events like disasters and epidemics. Although these events can impact tourism, they are difficult to predict and not the primary focus of the model. Ignoring them allows the model to concentrate on core variables and ensures feasible calculations.

3 Notations

The key mathematical notations used in this paper are listed in Table 1.

Table 1: Notations used in this paper

Symbol	Description	Unit
x_1	Number of visitors per day	Persons/day
x_2	Average spending per tourist	USD/person
x_3	Carbon emissions per visitor	Tons of CO2/person
x_4	Infrastructure consumption per visitor	Resource unit/person
x_5	Strategies to limit the number of visitors	Persons/day
x_6	Burden of living on the population	/
R	Total tourism revenue	USD
E	Environmental impact	Tons of CO2/person
P	Resident's burden	/

4 Model I：Sustainable Tourism Industry Model

The sustainability of the tourism industry may depend on factors such as the number of tourists, the overall income, and the measures taken to promote the stable development of the tourism industry. Since there are many factors at both explicit and implicit levels that play different roles in the sustainable development of the tourism industry, we also need to select important indicators of broad applicability to model the sustainable tourism industry, so as to reflect which factors are most representative of the tourism industry's ability to develop in a sustainable manner.

Each statistical indicator reflects part of the information of the sustainable development capacity of the tourism industry, but not all of the information is the main information, and due to the correlation between the statistical indicators, it is necessary to downsize and simplify, and extract some potential comprehensive indicators to describe the sustainable development capacity of the tourism industry. For this we use principal component analysis to deal with statistical indicators and use several composite indicators to fully reflect the information carried by each indica-tor. Principal component analysis is a dimensionality reduction algorithm that converts multiple indicators into a few principal components, which are linear combinations of the original variables and are uncorrelated with each other, and which reflect most of the information of the original data. In the constructed comprehensive evaluation model, the weights of each principal component are its contribution rate, which reflects the proportion of the amount of information of that principal component containing the original data to the total amount of information, and it is more objective and reasonable to determine the weights in this way.

Furthermore, the results obtained from dimensionality reduction using Principal Component Analysis (PCA) serve as an important reference for establishing the sustainable tourism industry model. To optimize the sustainable development of the tourism industry, we need to find the optimal solution that balances multiple objectives, which essentially transforms the problem into a multi-objective planning issue, considering various realistic constraints. Therefore, the original problem is reformulated as a dynamic model that reflects changes in the tourism industry system, based on the determined optimization objectives and established constraints. The Multi-Objective Particle Swarm Optimization (MOPSO) algorithm is used to solve the problem, which, compared to traditional multi-objective optimization methods, offers greater adaptability, stronger global search capabilities, and does not rely on derivatives of the objective function. This makes MOPSO particularly advantageous when dealing with complex, nonlinear problems with many constraints, as required in this study. Additionally, MOPSO provides a set of Pareto optimal solutions, enabling us to make more comprehensive choices among multiple objectives and offering richer decision-making support.

Finally, to illustrate how additional income contributes to the sustainable tourism model, we incorporated a feedback mechanism into the system and formulated corresponding expenditure plans. Sensitivity analysis of the model parameters was conducted to identify the factors that have the most significant impact on the sustainable tourism industry model.

4.1 Data Collection and Extraction

We collected data related to indicators from major websites and based on relevant references as well as tourism reports, we set the following eleven indicators: waste emissions, air index, greenhouse gases, traffic flow, population, labor force, carbon dioxide, median per capita income, hotel tax revenue, number of tourists, and number of people in poverty. The data sources are shown in Table 2.

Table 2: Data source collation

Data Names	Database Websites
Air Index, Carbon Dioxide, Waste Emissions	https://www.epa.gov/ghgreporting
Population	https://www2.census.gov/programs-surveys/popest/tables
Median Per Capita Income, Rate of Poverty	https://www.census.gov/programs-surveys/acs/data/data-via-ftp.html
Labor Force	https://www.bls.gov/lau/
Hotel Tax Revenue, number of tourists, traffic flow	CBJ-Tourism-Survey-2023-Report-12.11.23

4.2 Principal Component Analysis

4.2.1 Basic Principal of PCA

We use $x_1, x_2, ..., x_p$ to represent the P indicators: waste emissions, air index, greenhouse gases, traffic flow, population, labor force, carbon dioxide, median per capita income, hotel tax revenue, number of tourists, and number of people in poverty, $c_1, c_2, ..., c_p$ denote the weight of each indicator. Then the weighted sum $s(s = c_1 x_1 + c_2 x_2 + ... + c_p x_p)$ is the sustainable tourism industry model. We would like to assign appropriate weights to better characterize the sustainable tourism industry model. Each factor corresponds to one such composite indicator, $s_1, s_2, ..., s_n$, n represents the number of regions. Therefore, we need to find the appropriate $c_1, c_2, ..., c_p$ so that $s_1, s_2, ..., s_n$ can be dispersed as much as possible. To avoid the circumstance which the weight value can be chosen to be infinite and meaningless, it is stipulated that:

$$c_1{}^2 + c_2{}^2 + ... + c_p{}^2 = 1 \tag{1}$$

In addition, there is more than one measure of the level of sustainability of the tourism industry, i.e., one principal component is not enough to represent the original P variables, so it is necessary to find the second, third or even fourth principal component, and the second principal component should no longer contain the information of the first principal component, which is described mathematically and statistically as making sure $cov(z_1, z_2) = 0$, and geometrically as the direction of these two principal components being orthogonal. The specific method to determine the two principal components is as follows.

Let z_i be the i -th principal component, $i = 1, 2, .., p$, then:

$$\begin{cases} z_1 = c_{11} x_1 + c_{12} x_2 + ... + c_{1p} x_p \\ z_2 = c_{21} x_1 + c_{22} x_2 + ... + c_{2p} x_p \\ .... \\ z_p = c_{p1} x_1 + c_{p2} x_2 + ... + c_{pp} x_p \end{cases} \tag{2}$$

For each of these i , we got

$$c_{i1}{}^2 + c_{i2}{}^2 + ... + c_{ip}{}^2 = 1 \tag{3}$$

4.2.2 Normalization of Indicator Variables

Before the principal component analysis, it is usually necessary to standardize each indicator variable, so as to avoid the unreasonable selection of the unit of equally important variables, which makes the variance of the unit huge, thus giving unreasonable principal component analysis results. Usually $\tilde{X} = \dfrac{X_{ij} - E(X_i)}{\sqrt{D(X_i)}}$ is used to standardize indicator variables.

4.2.3 Steps of Principal Component Analysis

①Standardize raw index date

$$\tilde{X} = \frac{X_{ij} - \bar{X}_i}{S_i} \tag{4}$$

$$\bar{X}_i = \frac{1}{n} \sum_{j=1}^{n} x_{ij} \qquad i = 1, 2, ..., n \tag{5}$$

$$S_i{}^2 = \frac{1}{n} \sum_{j=1}^{n} (x_{ij} - \bar{x}) \qquad i = 1, 2, ..., n \tag{6}$$

Get standardized date matrix

$$\tilde{X}=\begin{pmatrix}\tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1p}\\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2p}\\ \vdots & \vdots & \dots & \vdots\\ \tilde{x}_{n1} & \tilde{x}_{n2} & \dots & \tilde{x}_{np}\end{pmatrix} \tag{7}$$

②Establish the correlation coefficient matrix R between the variables

$$R=(r_{ij})_{m\times m} \tag{8}$$

$$r_{ij}=\frac{\sum_{k=1}^{n}\tilde{x}_{ki}\cdot\tilde{x}_{kj}}{n-1},\quad (i,j=1,2,\dots,m) \tag{9}$$

Among them $r_{ii}=1, r_{ij}=r_{ji}$, r_{ij} is the correlation coefficient between the i-th indicator and the j-th indicator.

③Calculate the eigenvalues and eigenvectors of the correlation coefficient matrix R

Solve the eigenvalues and eigenvectors of R Solve the characteristic value $\lambda_1\geqslant\lambda_2\geqslant\dots\geqslant\lambda_p\geqslant 0$ from $(\lambda I-R)=0$, and then calculate the characteristic vector $l_1,l_2,\dots,l_p,l_i=(l_{i1},l_{i2},\dots,l_{ip})^T$ from $(\lambda I-R)=0$.

④Get the principal components and calculate the composite score

Calculate the contribution rate $p_i=\lambda_i\Big/\sum_{i=1}^{p}\lambda_i$ and cumulative contribution rate $\sum_{j=1}^{k}p_j=\sum_{i=1}^{k}\lambda_i\Big/\sum_{i=1}^{p}\lambda_i$ of each principal component, and determine the number m of principal components to be used according to the 0.85 principle. Then write the expression of the principal component $Y_i=l_{i1}\tilde{X}_1+l_{i2}\tilde{X}_2+\dots+l_{ip}\tilde{X}_p$. In order to make the principal component easier to explain, the load matrix of the principal component is rotated, and the maximum variance method is used to adjust the principal component load matrix after rotation.

4.2.4 Results

The KMO (Kaiser-Meyer-Olkin) value calculated for the 11 factors affecting the sustainable development of the tourism industry is 0.913, and the significance value of the Bartlett's dispersion test is 0.0091, which indicates that the data are suitable for principal component analysis.

Through principal component analysis, the principal component contribution ratio of the 11 factors can be obtained. As can be seen from Table 3, the cumulative contribution of the first three principal components exceeds 90%. Principal components can use fewer indicators to reflect the information reflected by the original more indicators, so this paper selects the first three principal components to represent the original 11 factors.

Table 3: Principal component contribution rate

No.	Variance	Contribution rate /%	Cumulative contribution rate /%
1	3.234	46.197	46.197
2	2.054	29.338	75.535
3	1.130	16.146	91.680
4	0.302	4.319	95.999

No.	Variance	Contribution rate /%	Cumulative contribution rate /%
5	0.167	2.383	98.383
6	0.106	1.514	99.897
7	0.007	0.103	100.000

The degree of correlation between the first three principal components and the sustainable development level of the tourism industry is shown in Figure 3 and Table 4, and the eigenvalues reflected by each principal component are as follows:

1) The first principal component mainly reflects: median per capita income, hotel tax revenue, number of tourists, and these composite indicators mainly reflect the local tourism income.

2) The second principal component mainly reflects: greenhouse gases, air index, carbon dioxide, waste emissions, reflecting the impact of tourism development on the environment.

3) The third principal component reflects the number of poor people, population, labor force, traffic flow, which mainly reflects the burden on local residents.

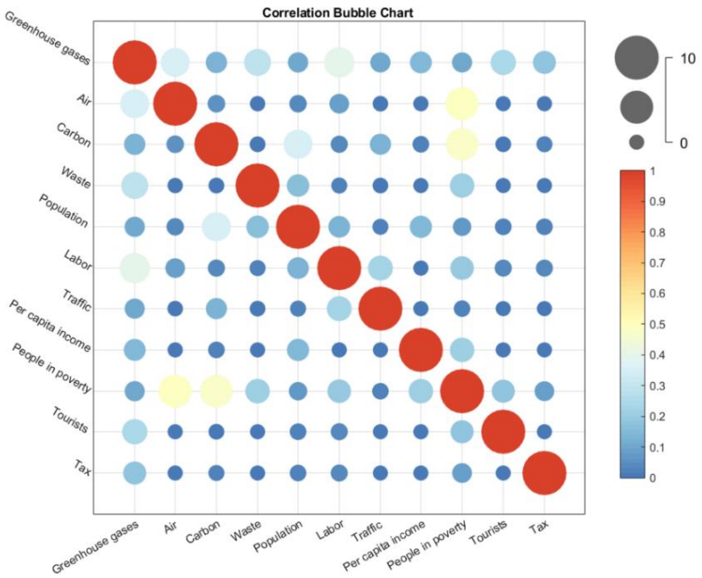

Figure 3: Correlation Analysis Bubble Matrix Diagram

Table 4: Principal component load matrix after rotation

Sustainable Tourism Industry Factors	The first principal component	The second principal component	The third principal component
X_1	-0.139	0.232	0.910
X_2	-0.813	0.215	-0.098
X_3	0.715	0.041	0.537
X_4	-0.900	0.073	0.039
X_5	-0.291	0.855	0.058
X_6	0.735	0.640	-0.153
X_7	-0.720	0.527	0.234
X_8	0.957	-0.026	-0.235
X_9	0.121	-0.703	-0.319
X_{10}	0.949	-0.290	-0.023
X_{11}	0.935	-0.314	-0.106

The principal components of the influencing factors of sustainable tourism industry were analyzed using SPSS software to eliminate possible multicollinearity between variables and extract as much sample information as possible. Since SPSS software standardized the raw data during the dimensionality reduction process to eliminate the effect of dimensionality, principal component component diagrams and gravel diagrams were obtained.

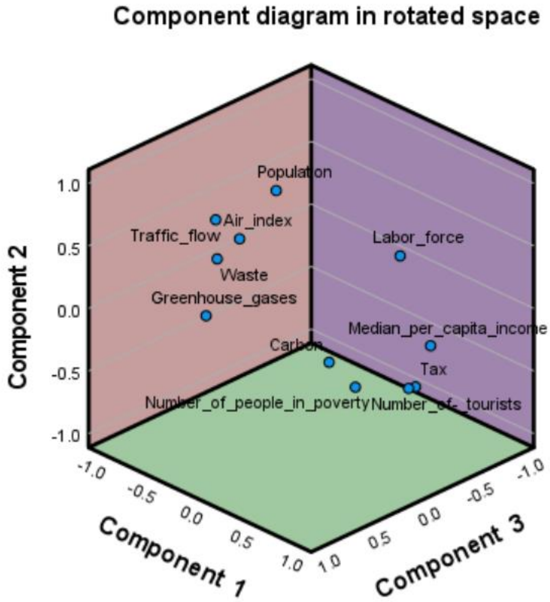

Figure 4: Component diagram in rotated space

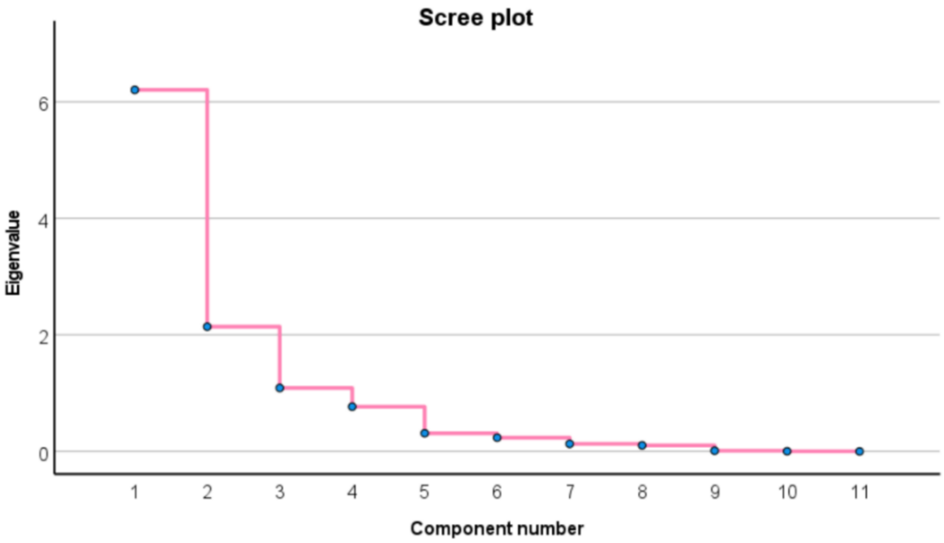

Figure 5: Gravel diagram of principal component analysis

At this point, we have obtained three main components through principal component analysis, which are tourism revenue R , environmental impact E , and residents' burden P . These three components are expressed through the eleven factors mentioned earlier as shown in the following equation.

$$\begin{cases} R = -0.139x_1 - 0.813x_2 + 0.715x_3 - 0.900x_4 - 0.291x_5 + 0.735x_6 - 0.720x_7 + 0.957x_8 + 0.121x_9 + 0.949x_{10} + 0.935x_{11} \\ E = 0.232x_1 + 0.215x_2 + 0.041x_3 + 0.073x_4 + 0.855x_5 + 0.640x_6 + 0.527x_7 - 0.026x_8 - 0.703x_9 - 0.290x_{10} - 0.314x_{11} \\ P = 0.910x_1 - 0.098x_2 + 0.537x_3 + 0.039x_4 + 0.058x_5 - 0.153x_6 + 0.234x_7 - 0.235x_8 - 0.319x_9 - 0.023x_{10} - 0.106x_{11} \end{cases} \tag{10}$$

It can be seen that the original 11 factors can be represented by the three main elements of revenue R , environmental impact E , and residents' burden P , so revenue R , environmental impact E , and residents' burden P is chosen as the decision variable, the corresponding objective function is established, and the three independent single-objective planning problems are integrated and transformed into multi-objective planning problems.

4.3 Multi-Objective Particle Swarm Optimization

For the primary components obtained in the previous section, they are used as decision variables in the multi-objective planning problem in this section, and constraints are established for the realistic influence conditions of each decision variable. And then the objective function and constraints are integrated to form a complete sustainable tourism industry model. And through the multi-objective particle swarm algorithm to simulate the foraging behavior of birds in nature, the location of food is analogous to the optimal solution set of the problem, and the flight direction and position of birds are analogous to the speed and position of particles. According to the information interaction between the global best (gBest) and individual historical best (pBest), the positions and velocities of the particles are constantly updated, which improves the search efficiency and effectively guides the population to converge in the direction of PF.

✧ **Optimization Objectives**

① **Maximizing Tourism Revenue**

The sources of revenue R mainly include direct spending by tourists (e.g., tickets, hotels, restaurants, etc.) as well as indirect spending driven by tourists (e.g., employment, sales of local goods, etc.). To this end, we introduce the consumption function and multiplier effect in economics, assuming that the relationship between the number of tourists and the level of consumption can be expressed in the following form：

$$R = f(x_1, x_2) = c_1 x_1 x_2 (1 + \mu x_1) \tag{11}$$

where c_1 is the average spending per tourist and μ is the spending multiplier, which indicates the contribution of the number of tourists to the local economy. This revenue function reflects the fact that the increase in tourists not only directly leads to spending, but also has a multiplier effect by stimulating the local economy and boosting total revenue.

② **Minimize Environmental Impact**

Environmental impacts include carbon emissions, resource consumption and other factors, and, drawing on the Environmental Kuznets Curve (EKC) theory in environmental studies, we hypothesize that the environmental impacts of tourists' activities increase and then decrease with the increase in the number of tourists. Specifically, carbon emissions E_{CO_2} and resource consumption $E_{resource}$ can be expressed as follows：

$$E_{\mathrm{CO_2}} = c_2 x_1 x_3 \tag{12}$$

$$E_{resource} = c_3 x_1 x_4 \tag{13}$$

The overall environmental burden E is the weighted sum of carbon emissions and resource consumption.

$$E = \lambda_1 E_{\mathrm{CO_2}} + \lambda_2 E_{\mathrm{resource}} = \lambda_1 c_2 x_1 x_3 + \lambda_2 c_3 x_1 x_4 \tag{14}$$

where λ_1 and λ_2 are weighting coefficients for environmental impacts, reflecting the weight of carbon emissions and resource consumption in the overall environmental impact.

In order to introduce the environmental Kuznets curve effect, we set a quadratic relationship between the environmental burden and the number of tourists, set as.

$$E = \alpha x_1^2 + \beta x_1 + \gamma \tag{15}$$

where α , β , γ and γ are regression coefficients used to characterize the relationship between the number of tourists and environmental impacts. This quadratic model indicates that when the number of tourists is low, the environmental impact increases with the number of tourists; after the number of tourists reaches a certain threshold, the environmental impact decreases with the number of tourists after effective management measures are taken.

③ Minimizing The Burden on Residents

The burden of residents mainly comes from the occupation of infrastructure by tourists, noise, congestion and other problems. By analyzing the social cost function, there is a positive relationship between residents' burden P and the number of tourists x_1 .

$$P = \gamma_1 x_1 x_6 \tag{16}$$

Where γ_1 is the resident burden coefficient, which reflects the impact of each tourist on the quality of life of local residents, x_6 represents the affordability of residents. Resident burden increases with the number of tourists.

✧ **Constraints**

① Restrictions on The Number of Tourists

Juneau has a limited capacity and the number of visitors cannot exceed the maximum capacity $x_1^{\max}$, so the following constraints apply：

$$x_1 \leqslant x_1^{\max} \tag{17}$$

$x_1^{\max}$ based on the City of Juneau's tourism statistics, derived from the average daily visitor arrivals during the peak tourist season as reported by the Juneau City Tourism Office. Set maximum visitor capacity at 5,000 per day.

② Environmental Impact Constraints

In order to maintain environmental sustainability, the total carbon emissions and resource consumption of tourists cannot exceed the set value $E_{\max}$, thus there are:

$$E = \lambda_1 c_2 x_1 x_3 + \lambda_2 c_3 x_1 x_4 \leq E_{\max} \tag{18}$$

$E_{\max}$ from Environmental Impact Assessment Technical Guidelines (HJ2.2-2018), in conjunction with the City of Juneau's Environmental Carrying Capacity Assessment. Set the maximum allowable value for environmental impacts at 1,000 tons of CO_2 per year.

③ Infrastructure Consumption Constraints

The infrastructure cannot be consumed beyond its maximum carrying capacity $F_{\max}$, as follows:

$$F = c_3 x_1 x_4 \leq F_{\max} \tag{19}$$

$F_{\max}$ from the study of urban residents' public service satisfaction and its influencing factors - based on CGSS2015 empirical analysis. Set the infrastructure consumption of each visitor as 0.5 resource unit/person and the maximum infrastructure consumption as 250,000 resource units per year.

④ Resident Burden Constraints

The burden on residents must not exceed an acceptable upper limit of $P_{\max}$, as follows：

$$P = \gamma_1 x_1 x_6 \leq P_{\max} \tag{20}$$

✧ **Sustainable Tourism Industry Model**

The above objective function and constraints are integrated into a complete sustainable tourism industry model, and the complete model is shown below:

$$\max z = R - E - P$$

$$s.t.\begin{cases} R = c_1 x_1 x_2 (1 + \mu x_1) \\ E = \lambda_1 c_2 x_1 x_3 + \lambda_2 c_3 x_1 x_4 \\ P = \gamma_1 x_1 x_6 \\ x_1 \leqslant x_1^{\max} \\ E = \lambda_1 c_2 x_1 x_3 + \lambda_2 c_3 x_1 x_4 \leq E_{\max} \\ F = c_3 x_1 x_4 \leq F_{\max} \\ P = \gamma_1 x_1 x_6 \leq P_{\max} \\ x_1, x_2, x_3, x_4, x_5, x_6 \geqslant 0 \end{cases} \tag{21}$$

At this point, we have obtained the formulation model of sustainable tourism industry, due to the multi-objective particle swarm algorithm (MOPSO) has the characteristics of simple operation and fast speed, here we will use MOPSO algorithm to calculate the optimal solution of the multi-objective planning problem.

Step1 Population initialization

Initialize the velocities and positions of all particles. Calculate the objective function for all particles, and form the pareto solution set by existing the non-inferior solutions of them in an external archive.

Step2 Determine individual optimality and group optimality

If $f(x_i)$ dominates the current personal best $f(pBest_i)$, update $pBest_i = x_i$. Identify the global best solution $gBest$ from the Pareto front, which is the best solution across the population.

Step3 Update inertia weight

Adjust the inertia weight ω to balance exploration and exploitation:

$$\omega = \omega_{\text{initial}} \cdot \left(1 - \frac{t}{T_{\max}}\right) \tag{22}$$

where t is the current iteration and $T_{\max}$ is the total number of iterations.

Step4 Update the velocity and position of particles

Velocity update:

$$v_i = \omega v_i + c_1 \cdot rand_1 \cdot (p\ \text{Best}\ _i - x_i) + c_2 \cdot\ \text{rand}_2 \cdot (g\ \text{Best}\ - x_i) \tag{23}$$

where c_1 and c_2 are acceleration coefficients, and $rand_1$, $rand_2$ are random numbers.

Position update:

$$x_i = x_i + v_i \tag{24}$$

Step5 Cross mutation operation

Introduce diversity by applying crossover and mutation, which may involve: Exchange segments of positions between two particles and randomly modify a particle's position to explore new areas.

Step6 Calculate the fitness of particles and update the Pareto optimal solution set

Recalculate the objective values for each particle $f(x_i)$,then compare the current solutions with the external archive, updating it with the non-inferior solutions.

Step7 Update the group optimum and individual optimum

For each particle, if the new solution dominates the current $pBest_i$,update it.Choose the best solution in the Pareto front as $gBest$ to guide the swarm.

Step8 Iteration termination judgment

Check if the iteration requirements are met. If they are met, output the result. If not, return to step 3.

Through iterative calculation, the Pareto cumulative graph obtained is shown in Figure 6, and the optimal solution set at this time is 6594 daily tourists, per capita tourism consumption of 1800 US dollars, emissions plus waste emissions of 0.54 tons, limiting the number of tourists to 10000, basic resource consumption of 500 US dollars, total tourism revenue of 392482089.337264 US dollars, environmental impact of 29707 tons, and local resident burden index of 0.03215.

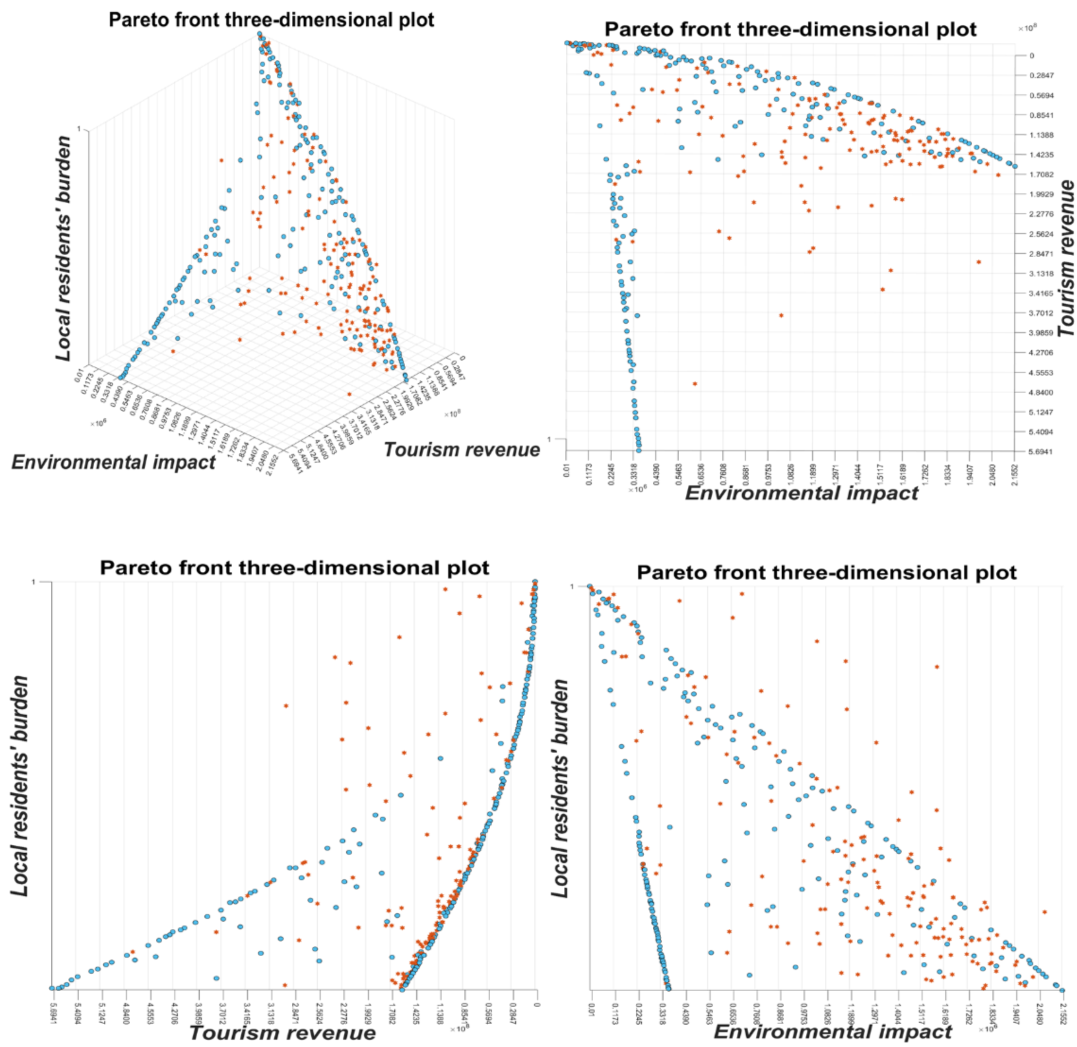

Figure 6: Pareto front three-dimensional plot

4.4 Expenditure feedback system for additional income

Juno city has taken various measures to cope with the negative impact of tourism development, including increasing hotel taxes, levying tourist fees, limiting daily tourist numbers, and restricting alcohol sales and consumption. The additional income obtained through taxation will be used to support conservation work, improve infrastructure, and develop community projects. Based on this, we have designed a feedback mechanism system for additional income to be used for expenses, in order to help Juno City better plan its expenditures. The additional income and expenditure plan can be expressed as:

$$I_{\text{total}} = \alpha \times R \tag{25}$$

Where,

$$I_{\text{total}} = I_{\text{eco}} + I_{\text{infra}} + I_{\text{community}} \tag{26}$$

Assuming that the tax revenue or hotel fee revenue collected is allocated proportionally to different expenditure items, it can be expressed as:

$$T_{env} = \alpha_{\text{env}} \cdot T, \quad T_{\text{infra}} = \alpha_{\text{infra}} \cdot T, \quad T_{\text{social}} = \alpha_{\text{social}} \cdot T \tag{27}$$

Where $\alpha_{env} + \alpha_{infra} + \alpha_{\text{social}} = 1$, T is the total amount of additional taxes.

Therefore, develop corresponding expenditure plans for additional income.

- **Environmental Protection (Ecological Restoration)**

$$I_{\text{eco}} = \beta_1 \times I_{\text{total}} \tag{28}$$

Among them, β_1 is the proportion of expenditure used for ecological restoration.

- **Infrastructure improvement**

$$I_{infra} = \beta_2 \times I_{\text{total}} \tag{29}$$

Among them, β_2 is the proportion of expenditure used for infrastructure improvement.

- **Community development**

$$I_{community} = \beta_3 \times I_{\text{total}} \tag{30}$$

Among them, β_3 is the proportion of expenditure used for community development.

After the expenditure is used for environmental protection and infrastructure construction, the feedback mechanism should reflect the improvement of tourist experience. This can be achieved through feedback on environmental protection, improving infrastructure, and promoting community development

➢ **Feedback on environmental protection**

$$E_{\text{new}} = E - \delta_1 \times I_{\text{eco}} \tag{31}$$

Among them, δ_1 is the proportion of reduction in the impact of ecological restoration on the environment.

➢ **Feedback on infrastructure improvement**

$$F_{\text{new}} = F - \delta_2 \times I_{\text{infra}} \tag{32}$$

Among them, δ_2 represents the reduction ratio of infrastructure improvement to consumption.

➢ **Feedback on community development**

$$P_{\text{new}} = P - \delta_3 \times I_{\text{community}} \tag{33}$$

Among them, δ_3 is the proportion of community development that reduces the burden on residents.

4.5 Sensitivity Analysis

By conducting sensitivity analysis on the overall tourism revenue and environmental impact, as shown in Figure 6, it can be found that the parameter changes of environmental impact have a higher degree of oscillation on the system as a whole than on the overall tourism revenue. From this, it can be concluded that it is not advisable to completely sacrifice environmental benefits for economic benefits, as it will cause irreparable damage to the sustainable development of the tourism industry system and cause destruction and impact on the overall sustainable development of the tourism industry system.

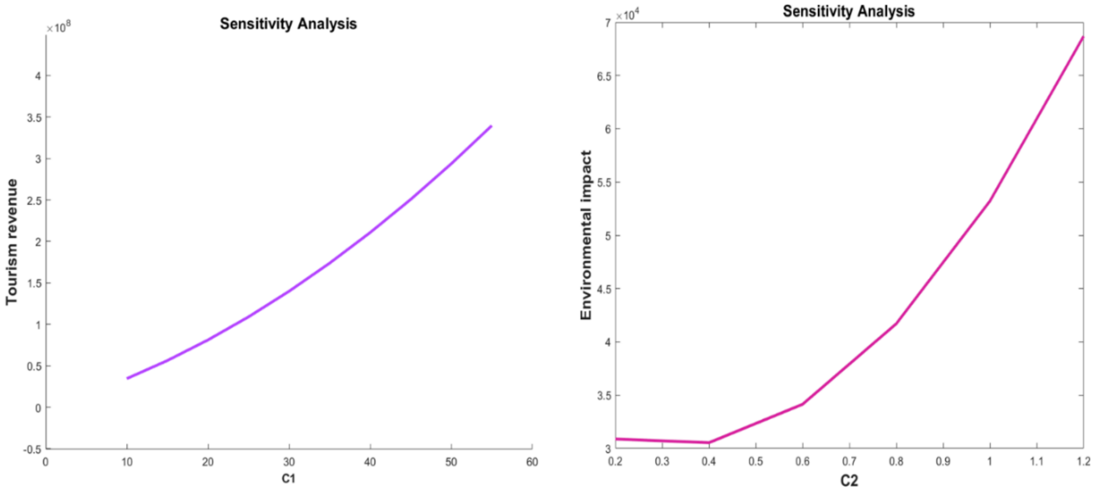

Figure 6: Pareto front three-dimensional plot

5 Model II: Tripartite Evolutionary Game Theory Model

The government department and the participants make strategic decisions, and the local government department has two choices: to regulate or not to regulate; the participants have the following two situations, one is to cooperate with the government and take measures to control light pollution, and the other is to cooperate with the government and take a negative attitude to control light pollution. In this game, if the local government does not regulate, the government will be punished in some way. Thus, the game payment matrix between the government and the participant group can be obtained, as shown in Table 5.

Table 5: The evolutionary game payment matrix

	Positive （y）	Negative （$1-y$）
Supervision （x）	（V_1-G,V_2+E-Q）	（V_1-G+F,V_2-F）
No supervision （$1-x$）	（V_1-H,V_2-Q）	（V_1-H,V_2）

Assume that $H,M,Q,G,N>0,M-Q>0,H-G>0$

where the benefit to the government can be expressed as V_1 ; then the benefit to the participants can be expressed as V_2 ; H denotes the penalty to the government if the government does not regulate; M denotes the reward given by the government when the participants take measures to promote the development of the tourism industry; Q denotes the investment of the participants (e.g., the cost of clearing surrounding) if the participants are positive attitude to cooperate with the government to develop tourism; N denotes the penalty given by the government if the participants do not take measures to develop tourism industry or deals with it passively; G indicates the cost required by the government to carry out regulation. If the participant actively participates in the sustainable tourism industry during government regulation $M-Q>0$,means the incentive given by the government to expand and develop the tourism industry. If $H-G<0$, that is, if the government does not regulate, the penalty imposed on the government is greater than the cost of regulation.

5.1 Replicated dynamic equations between government and participant

Assume that the probability of choosing a regulatory strategy is x and the probability of choosing a non-regulatory strategy is $1-x$ for the government group; the probability of choosing a positive strategy is y and the probability of adopting a negative strategy is $1-y$ for the participant group.

The expected benefits of the government's "regulatory" strategy is:

$$u_{11}=y(V_1-G)+(1-y)(V_1-G+N)=V_1-G+N-yN \tag{34}$$

The expected benefit when the government adopts a "no regulation" strategy is:

$$u_{12}=y(V_1-H)+(1-y)(V_1-H)=V_1-H \tag{35}$$

The average return to the government is:

$$\overline{u}_1=xu_{11}+(1-x)u_{12} \tag{36}$$

The expected benefit when participants adopt the "positive" attitude strategy is:

$$u_{21}=x(V_2+M-Q)+(1-x)(V_2-Q)=xM+V_2-Q \tag{37}$$

The expected benefit when the participant adopts the "negative" attitude strategy is:

$$u_{22}=x(V_2-N)+(1-x)V_2=-xN+V_2 \tag{38}$$

The average return for participants is:

$$\overline{u}_2=xu_{21}+(1-x)u_{22} \tag{39}$$

The replication dynamics of the two types of group games are analyzed separately, and the replicated dynamics equation of the government can be obtained as:

$$N_1(x,y)=x(u_{11}-\overline{u}_1)=x(1-x)(u_{11}-u_{12})=x(1-x)(H-G+N-yN) \tag{40}$$

The replication dynamics equation for the participant is:

$$N_2(x,y)=y(u_{21}-\overline{u}_2)=y(1-y)(u_{21}-u_{22})=y(1-y)(xN+xN-Q) \tag{41}$$

Let $N_1(x,y)=0$,and we get $x=0,x=1,y^*=(H-G+N)/N$ .Let $F_2(x,y)=0$,and we get $y=0,y=1,x^*=Q/(M+N)$.

The game between the government and the participants can be described by a system consisting of two differential equations (40), (41). This yields five equilibrium points:

$M_1 = (0,0), M_2 = (0,1), M_3 = (1,0), M_4 = (1,1), M_5 = (x^*, y^*)$.

5.2 Stability analysis between government and participants

The properties of the above five equilibria are tested according to the method proposed by Freedman. The method is to check the sign of the determinant $\det J$ and the sign of trJ of the Jacobi matrix J of the system of dynamic equations (40), (41). If the sign of $\det J$ is positive and the sign of trJ is negative, the corresponding equilibrium point is stable; if the sign of $\det J$ is positive and the sign of trJ is positive, the corresponding equilibrium point is unstable; if the sign of $\det J$ is negative, the corresponding equilibrium point is a saddle point.

The Jacobi matrix is:

$$J = \begin{bmatrix} \dfrac{\partial N_1(x,y)}{\partial x} & \dfrac{\partial N_1(x,y)}{\partial y} \\ \dfrac{\partial N_2(x,y)}{\partial x} & \dfrac{\partial N_1(x,y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)(H-G+N-yN) & -xN(1-x) \\ y(1-y)(M+N) & (1-2y)(xM+xN-Q) \end{bmatrix} \tag{42}$$

Substituting the five equilibrium points into the Jacobi matrix J, the calculation results are shown in Table 6.

Table 6: Equilibrium point property analysis

Balance point	$\det J$	Signs	trJ	Signs
(0,0)	$-Q(H-G+N)$	$-$		
(0,1)	$(H-G)Q$	$+$	$H-G+Q$	$+$
(1,0)	$-(H-G+N)(M+N-Q)$	$-$		
(1,1)	$(H-G)(M+N-Q)$	$+$	$-(H-G)-(M+N-Q)$	$-$
(x^*,y^*)		$-$	0	

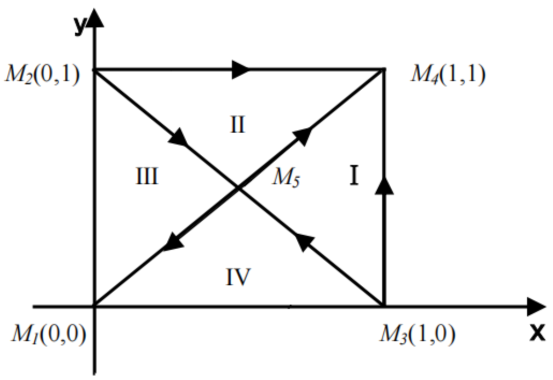

Figure 7: Reproduction of dynamic phase diagram

As can be seen from Table 6 and Figure 7, $M_2 = (0,1)$ is instability point, $M_1 = (0,0), M_3 = (1,0), M_5 = (x^*, y^*)$ are saddle points, $M_4 = (1,1)$ is stable point, It is the evolutionary stabilization strategy of the system (ESS), i.e., government regulation and active attitude of the participants. The final outcome of the evolutionary dynamic process depends on the initial state at the beginning of the game. The initial states are located in domains

I and II, and the system converges to $M_4 = (1, 1)$. We want to expand the regions I and II, and move the point M_5 to the lower left to increase the probability of convergence to $M_4 = (1, 1)$. When the point M_5 moves to the lower left, the value of x^* becomes smaller, and the value of y^* also becomes smaller, and x^*, y^* , are associated with the parameters Q, N, M, G, H .

5.3 Promotion and Application of Models - Taking Venice as an Example

For question two, we have chosen Venice as the research object. Venice has also suffered from environmental problems caused by the development of tourism in recent years. Based on the multi-objective programming model proposed in the previous question, we have updated the model applicable to Venice and incorporated the application of evolutionary game theory to promote a balance between local tourism and residents' lives.

✧ **Optimal Objective(Additional)**

During the Easter holiday on April 17, 2023, the number of tourists in Venice, Italy has returned to pre pandemic levels. The city government of Venice has implemented a plan since June to impose an entry fee of 3 to 10 euros on every tourist who does not stay overnight, in order to limit the number of tourists and combat the problem of excessive tourism.

$$R = f(x_1, x_2) = c_1 x_1 x_2 (1 + \mu x_1) + \psi x_1 \tag{43}$$

Among them, ψ is the entry fee for each tourist, representing the additional income brought by the entry fee policy.

✧ **Constraints(Additional)**

i. Water resources restriction

Venice, also known as the Water City, has suffered from severe water pollution due to the development of tourism. Therefore, it is necessary to consider the constraints of water pollution

$$W = \eta x_1 x_8 \leq W_{\max} \tag{44}$$

Among them, W represents the degree of water pollution, η is the proportionality coefficient, x_1 represents the number of tourists received per day, x_8 represents the level of activities related to water pollution, and $W_{\max}$ is the maximum allowable value of water pollution. According to the statistics released by the Venice Tourism Bureau, the maximum amount of water pollution is 600000 cubic meters.

ii. Entry fee system

We will incorporate the entry fee system as a new constraint condition into the model to limit the daily number of tourists. Specifically, we set a tourist quantity adjustment factor based on the entry fee, which reflects the impact of the entry fee on the number of tourists. For example, if the entry fee is 5 euros, this will reduce the number of tourists by a certain percentage, that is, 10%.

$$x_1 \leq (1 - \phi) \cdot x_1^{\max} \tag{45}$$

Among them, x_1 is the number of tourists received per day, $x_1^{\max}$ is the maximum number of tourists without being affected by the entry fee policy, and ϕ is the proportion of tourist reduction caused by the entry fee policy. According to the specific details of the policy, it can be a fixed value or a function that varies with the amount of entry fee. For example, if the entry fee is 3 euros, ϕ may be 0.05, indicating a 5% decrease in the number of tourists; If the entry fee is 10 euros, it may be 0.1, indicating a 10% decrease in the number of tourists. The population distribution of Venice is shown in Figure 8.

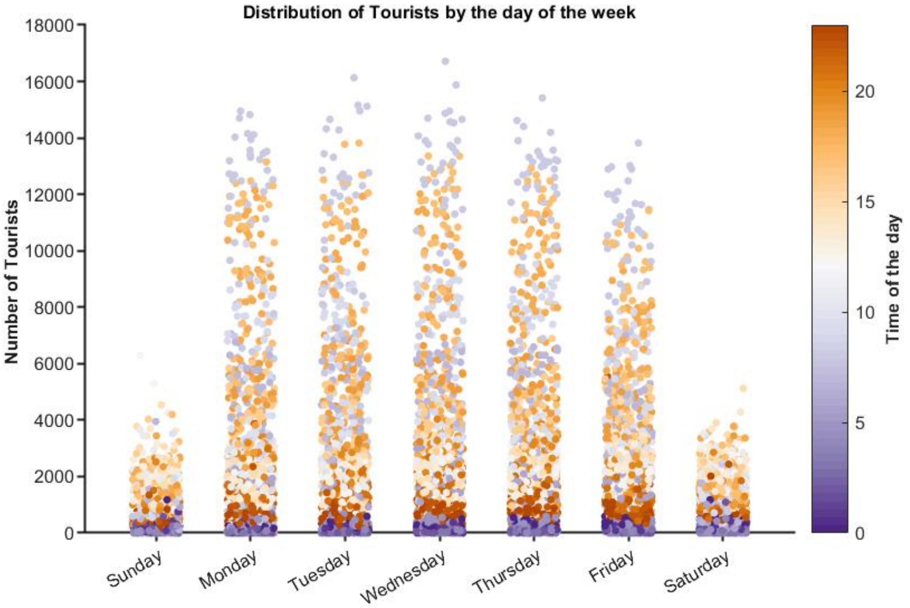

Figure 8: Distribution of tourists by the day of the week

At this point, evolutionary game theory is used to find the equilibrium point of the three parties, and the results obtained are shown in Figures 9:

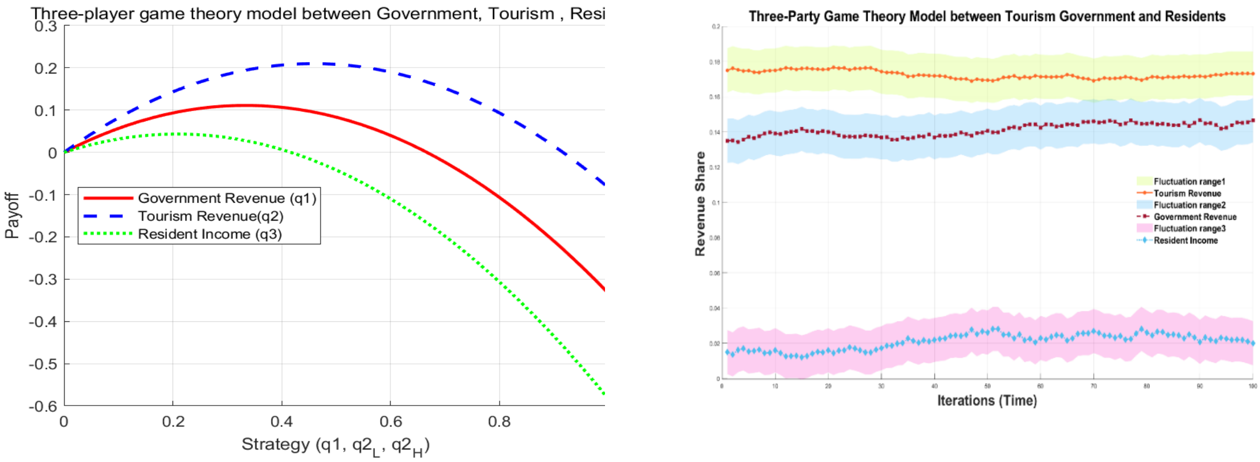

Figure 9: Game Theory Model between Government, Tourism, Residents

After calculation, the result shows that the daily number of tourists is 95634.6898495230, with an average tourism consumption of 2000 US dollars per person, 0.46232 cubic meters of water pollution, a limit of 98000 tourists, and a basic resource consumption of 580 US dollars. The tourism revenue is 91479070745.8490 US dollars, the environmental impact is 443225.145018339 cubic meters, and the burden on local residents is 0.13215. The profit distribution ratio is: tourism: 0.173128274139617 government: 0.146625156526524 residents: 0.0200181050259697.

6 Memo to The Tourist Council of Juneau

THE FINAL PREDICTIONS, EFFECTS OF VARIOUS MEASURES AND ADVICE ON HOW TO OPTIMIZE OUTCOMES

Dear Members of the Juneau Tourism Board,

Based on our multi-objective optimization model, we present the following summary of the model's predictions, current measures, and suggestions for optimization to balance tourism growth with environmental sustainability and resident welfare in Juneau.

1. Optimizing Visitor Management and Revenue Growth

The model suggests that while the current visitor limit is set at 10,000, significant increases in tourism revenue can be achieved by enhancing per capita spending and optimizing the structure of tourism activities. We recommend focusing on high-value tourist experiences and diversifying offerings to boost per visitor income, without dramatically increasing the number of visitors.

2. Implementing Low-Carbon Tourism and Green Development

The current environmental impact is calculated at 29,707 tons of CO2, and as tourism grows, this impact may escalate. Therefore, the board should prioritize low-carbon and green tourism initiatives. These may include encouraging eco-friendly transportation, reducing the carbon footprint per visitor, and promoting recycling and waste reduction efforts. Such measures would help mitigate the environmental burden and protect Juneau's natural resources from over-tourism.

3. Addressing Resident Welfare and Social Equity

The model indicates that resident burden remains relatively low (0.03215), but as tourism expands, the quality of life for locals may be affected. We recommend implementing policies that ensure a fair distribution of tourism revenue to residents, such as tax incentives or subsidies. This approach would reduce potential social tensions and ensure that local communities benefit from the growth of the tourism sector.

4. Balancing Stakeholder Interests

Using the evolutionary game theory model, we suggest optimizing the resource allocation between the government, the tourism industry, and local residents. A fair distribution of benefits will foster long-term cooperation and help develop a sustainable tourism ecosystem for Juneau. Implementing policies that share the tourism-derived economic benefits can prevent overdevelopment and ensure balanced growth.

5. Dynamic Monitoring and Sensitivity Analysis

To adapt to changing external factors, we recommend regular updates to the model and scenario simulations. Sensitivity analysis indicates the model's stability and effectiveness in providing reliable decision-making support. Real-time monitoring of tourism demand, environmental shifts, and other dynamic data will allow for timely adjustments to policies.

Conclusion

By integrating the recommendations from the multi-objective optimization model, Juneau can achieve sustainable tourism growth while ensuring environmental preservation and social equity. These strategies will enhance the long-term viability of the tourism sector, foster regional economic development, and improve the quality of life for residents.

We look forward to assisting the board with the implementation and further refinement of the model.

Sincerely,
Team/Control Number：2506398
2025.01.27

7 Model Evaluation

7.1 Strengths

A. Comprehensive Multi-Objective Optimization

The model effectively balances multiple objectives—economic growth, environmental protection, and social equity—providing a well-rounded solution for sustainable tourism development.

B. Data Efficiency through Dimensionality Reduction

By utilizing Principal Component Analysis (PCA), the model reduces the complexity of large datasets, highlighting the most influential factors and allowing for more focused and efficient decision-making.

C. Adaptability and Robustness in Complex Scenarios

The Multi-Objective Particle Swarm Optimization (MOPSO) algorithm enhances the model's ability to address nonlinear, constrained, and real-world complexities without relying on the derivatives of objective functions, ensuring practical applicability.

D. Fair Resource Allocation

The model applies Evolutionary Game Theory to optimize the distribution of resources among the government, tourism sector, and residents, ensuring a fair balance of interests and promoting long-term sustainable cooperation.

7.2 Weaknesses

A. Simplified Assumptions on Key Factors

The model assumes a linear relationship between tourist numbers and environmental impacts, and it overlooks factors like seasonal variations and diverse tourist behaviors, which may limit its accuracy in real-world conditions.

B. Exclusion of External Shocks and Uncertainty

The model neglects the impact of rare events, such as natural disasters or pandemics, which can significantly disrupt tourism, thus potentially underestimating risks and uncertainties.

C. Over-simplification of Resident Burden

Although the model accounts for resident burdens, it only provides a basic estimation and may not fully capture the broader social and economic impacts on local communities as tourism grows.

8 Conclusion

This study proposes a multi-objective optimization model for sustainable tourism development in Juneau, Alaska, aiming to balance economic growth, environmental protection, and social welfare. By integrating economic, environmental, and social factors into a unified decision-making framework, the model provides a comprehensive approach to managing tourism in the region. The use of Principal Component Analysis (PCA) for dimensionality reduction and Multi-Objective Particle Swarm Optimization (MOPSO) for solution search enhances the model's efficiency and adaptability, making it well-suited for handling complex, multi-faceted issues in sustainable tourism.

The key findings from the model suggest that, while limiting tourist numbers can help manage environmental impacts and resident burden, substantial gains in tourism revenue can still be achieved by optimizing factors like per capita spending and the structuring of tourism activities. Furthermore, the model's application of game theory highlights the importance of negotiating a fair distribution of benefits among stakeholders—government, tourism businesses, and local residents—ensuring that the benefits of tourism growth are equitably shared, and long-term sustainability is prioritized.

However, the study also acknowledges the limitations of the model, including its simplified assumptions about linear relationships between tourist numbers and environmental impact, the exclusion of unpredictable external shocks, and the over-simplification of resident burden. These factors suggest that the model should be periodically updated to account for dynamic changes in both the tourism industry and the broader socio-economic environment.

In conclusion, this research contributes to the ongoing effort to establish sustainable tourism models that are not only effective in fostering economic growth but also mindful of the environmental and social challenges posed by rapid tourism expansion. The insights gained can help guide future policy decisions and provide a framework for other tourist destinations grappling with similar sustainability challenges. By focusing on the most influential variables and integrating stakeholder interests, sustainable tourism practices can be realized, ensuring that tourism benefits are maximized while minimizing negative impacts on the environment and local communities.

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