Problem Chosen	2025 MCM/ICM Summary Sheet	Team Control Number
B		2520009

From Glaciers to Growth: A Sustainable Tourism Model for Juneau

Summary

While over-tourism generates short-term revenue for the City of Juneau, its hidden costs have a detrimental impact on long-term environmental sustainability. Therefore, it is crucial to explore measures that can promote sustainable tourism. This paper presents an optimization methodology for sustainable tourism that integrates environmental, economic, and social dimensions, making it applicable to a variety of regions.

Several models are established: Model I: **Passenger Numbers Prediction Model**; Model II: **CPR Sustainability Indicator Model**, etc.

For Model I, we established three sub-models to form the Passenger Numbers Prediction Model. At first, we build the **Autoregressive Prediction Model** to describe the relationship between passenger numbers and time using **one order ARIMA** model. According to the principle of **price elasticity of demand** in economics and with reference to the **Double-Log Demand Model**, we make a correction to the original equations. Finally, we constructed a relationship between visitor numbers and tourism sustainability based on a number of studies related to sustainable development, which led us to propose **Sustainability Revision Model**.

For Model II ,we concretely quantify tourism sustainability in order to establish the CPR Sustainability Indicator Model . First, we introduce the calculation of the total carbon footprint and infrastructure pressure, and develop an annual iterative model for these two factors through measures that First, we introduce the calculation of the total carbon footprint and infrastructure pressure, and develop an annual iterative model for these two factors through measures that **return additional tax revenues**. Secondly,We used **random forest method** to fit the relationship between residents' satisfaction and total revenue as well as passenger numbers. Finally, we normalized the three factors after performing a positive transformation, and determined the weight of each factor based on the actual conditions of the study area. The weighted values were then used to calculate the sustainability indicator.

After that, we optimize the whole model using **Particle Swarm Optimization (PSO)** to give numerical optimum solution to the sustainable tourism revenue in a long term. And the optimal tax rate have been solved as follows:

- For Juneau, we obtain the optimal tourism management scheme, the maximum number of passengers per year in our plan is **1.85 million**, and the tax rate in the optimized plan is shown in **Figure6**. By investing additional tax revenues in sustainable conservation, the optimization rate of the total revenues reaches **6.9%** and **73%** in years 50 and 100, respectively, indicating that these expenditures contribute significantly to tourism development in the long term.
- For Barcelona, We adjust the weights of the three factors based on local situation and find a stable results in **Section 5.2**. In the optimized plan, the maximum number of passengers per year is **1.94 million**, and the tax rate is shown in **Figure9**. For Chamdo, Tibet with fewer tourists the revenue displays a cyclical process of 'low tax growth - stable tax collection - low tax growth'. The optimization of total revenue reached **34%** and **38%** in year 10 to 50 and 50 to 83, respectively.

Finally, we analyzed the sensitivity and stability of the model and wrote a memo to the Juneau Tourism Commission based on the model scenarios and prediction results.

Keywords:ARIMA,Double-Log Demand, Random Forest Method,PSO,

Contents

1 Introduction

1.1 Problem Background

As the capital of Alaska,also one of its most beautiful cities and one of the most visited communities in the state,there's so much to see and do for you in Juneau.In 2023 this small city of 30,000 residents recorded 1.6 million cruise ship passengers, bringing in $375 million in revenue,There is no doubt that the tourism industry has become a pillar of the local economy.

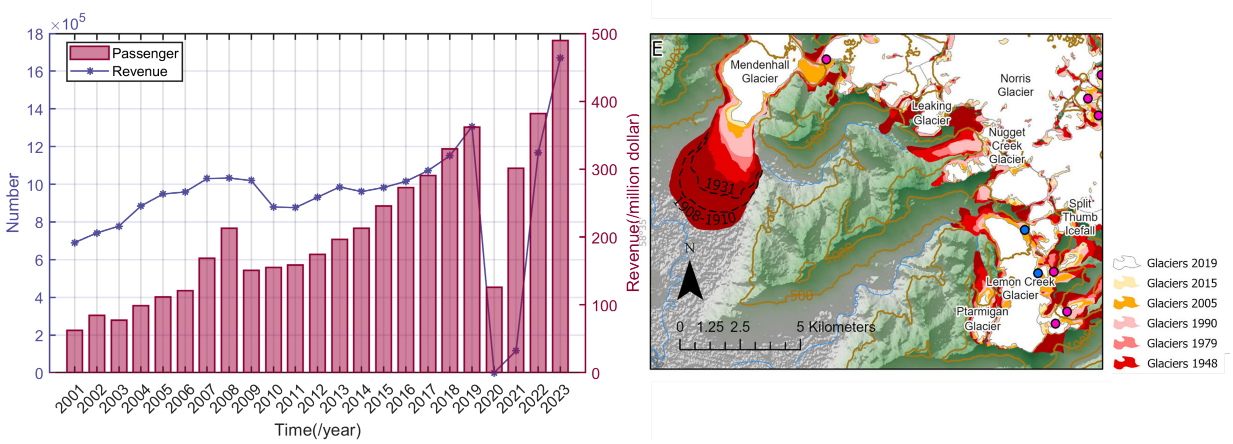

Figure 1: Historical passenger numbers and total tourism revenue in Juneau (left) and glacier melt (right)

The left side of the image above shows the number of visitors to Juneau and the total revenue generated in previous years, while the right side shows the evolution of the Juneau Icefield over time, showing that overtourism not only generates revenue for Juneau, but also contributes to the degradation of the glaciers in the area.There are also problems such as pressure on infrastructure, increased carbon footprint from tourist activities, and pressure on local populations due to housing supply and costs, collectively referred to in recent reports [1] as the hidden costs of tourism. It is therefore vital to enact measures and invest to support conservation and to explore how sustainable tourism can be developed while maintaining local incomes.

1.2 Restatement of the Problem

Under the above background, and in order to help juneau achieve the goal of sustainable tourism, our group will accomplish the following tasks:

(1) Construct a sustainable tourism model in Juneau, considering factors such as the number of tourists,total revenue,measures to stabilize the tourism industry. Clarify optimisations and constraints, and include a plan to rebate expenditure from additional revenue,Include a sensitivity analysis and discuss the most important factors.

(2) Apply the model to another destination affected by overtourism, illustrating how the choice of location affects the most important measures, and use the model to promote a more balanced development of sites with fewer tourists.

(3) Write a one-page memo to the Juneau tourism council, state our predictions, the effects of the measures, and suggestions for optimising the outcomes.

1.3 Literature Review

This section focuses on the implications of sustainable tourism. In recent years, research on sustainable tourism has focused on the triple bottom line approach and related basic models.

➢ As of approaches,TBL provides a framework for measuring the performance and success of the organisation using the economic and success of the organisation using the economic, social and environmental lines[2].First,the economic line of the TBL framework refers to the impact of the organisation's business practices on the economic system [3].Aecond,the social line refers to conducting beneficial and fair business practices for labour, human capital and the community [3].Finally,the environmental line refers to engaging in practices that do not compromise environmental resources for future generations.

➢ As for the basic models, the environmental sustainability indicators, the double logarithmic demand model and the social satisfaction model are the most commonly used models in related studies, and it is worth noting that both the double-log demand model with correction effects[4] and the integrated environmental sustainability indicators [5]describe only one dimension of either the economy or the environment, and therefore we need to combine and improve them.

The advantages and disadvantages of the three basic models are shown below.

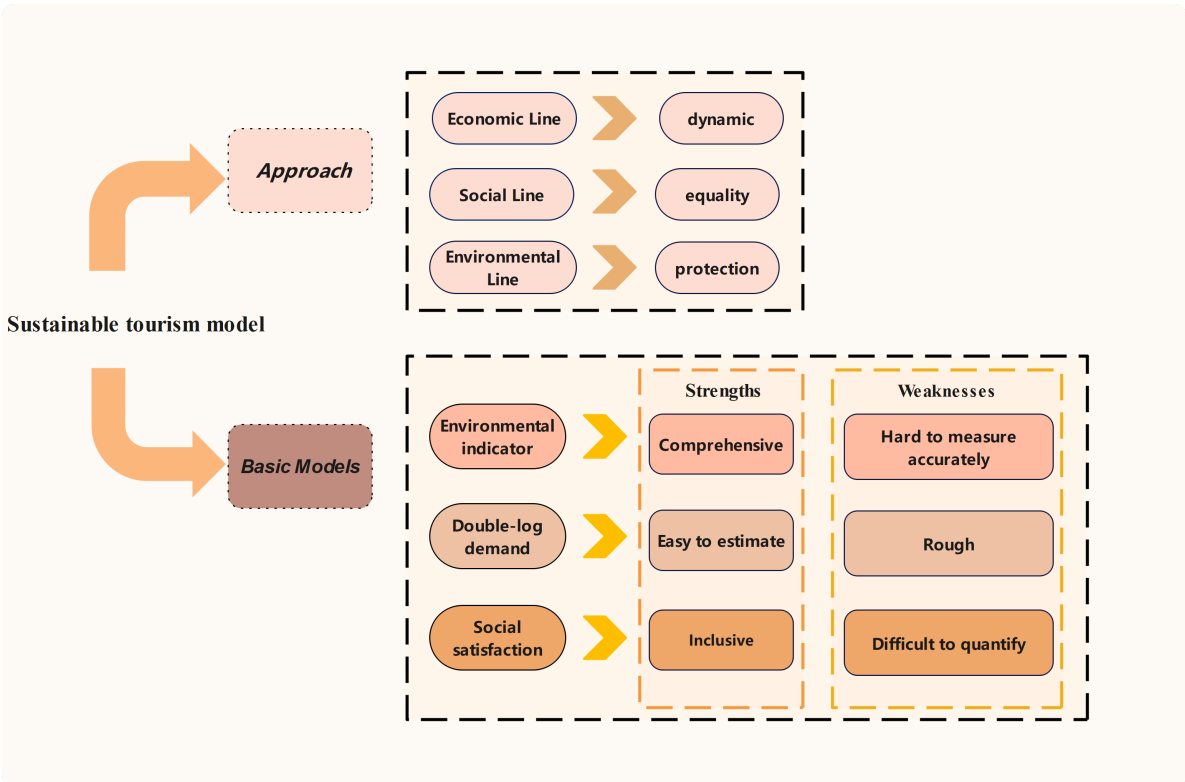

Figure 2: Literature Review

1.4 Our Work

Our solution mind map is shown below.

2 Assumptions and Justifications

Assumptions are made as follows to simplify the problem. Each of them is properly justified.

- **Assumption1: The time for visitors to reside in Juneau is negligible.**

  ↪ **Justification:** Our model calculates in years, so finer time scales will not be considered. The only time we primarily consider is the time we rely on income tax receipts for that period to designate the following year's budget.

- **Assumption2: All additional revenues from taxes are used to support conservation, make improvements in infrastructure, and develop community programs.**

  ↪ **Justification:** Based on our definition, Juneau's tourism revenue is categorized as both base (covering costs and fiscal revenues) and additional revenue (supporting conservation, infrastructure, and community programs).

- **Assumption3: Ignoring major natural disasters and human impacts.**

  ↪**Justification:** Since major natural disasters and human disturbances are difficult to predict, such as the 2020 COVID-19 pandemic, our model does not take them into account.

- **Assumption4: Impact on Juneau's local environment by carbon footprint of other regions is negligible.**

  ↪**Justification:** Due to Juneau's geographic isolation and relatively small population, while global warming from global carbon emissions affects Juneau's glaciers and climate, the direct impact of carbon emissions from other regions on the local environment is negligible compared to local carbon emissions.

- **Assumption5: The income generated from the carbon footprint tax cannot be reinvested into carbon footprint reduction efforts in the current year.**

  ↪**Justification:** The fiscal year and budget cycle are typically separate and budget's reliance on current year revenues creates a circular dependency. As a result, accurate financial forecasting and management is difficult if we reinvest the carbon footprint tax into carbon footprint reduction efforts in the current year.

3 Model Preparation

3.1 Notations

The primary notations used in this paper are listed in Table 1.

Table 1: Notations used in this paper

Symbols	Description
N_t	Final predicted number of passengers as a function of time
N_t^i	Preliminary or Adjusted predicted number of passengers as a function of time
P_t	The actual price per capita as a function of time
C_t	Total carbon footprint as a function of time
I_t	Infrastructure capacity as a function of time
Q_t	Infrastructure pressure as a function of time
R_t	Residents' satisfaction indicator as a function of time
T_t	Total revenue including hidden costs as a function of time
$a_{1,t}$	Carbon footprint tax rates as a function of time
$a_{2,t}$	Infrastructure tax rates as a function of time
S_t	Sustainability indicator as a function of time
E_p	Price elasticity of demand
$Cost$	The average individual cost
M	Annual maximum passenger number
$\bar{c}$	The average carbon footprint per tourist

Note:There are some variables that are not listed here and will be discussed in detail in each section.

3.2 Data Collection

This article relies on the following table of data sources.

Table 2: Data and Database Websites

Database Names	Database Websites
GDP by State	https://www.bea.gov/data/gdp/gdp-state
Center for Sustainable Systems	https://css.umich.edu/publications/factsheets/sustainability-indicators
Alaska Science Center	https://www.sciencebase.gov/catalog/item/5d5b1328e4b01d82ce8ed3a2
OpenStreetMap	https://www.openstreetmap.org/

- From GDP by State, we obtained Juneau's year-to-year tourism revenues from 2001 through 2023.
- From Center for Sustainable Systems, we obtained the GHG emissions of an individual in the U.S on a per capita basis.
- From Alaska Science Center, we obtained Juneau Ice Sheet glacier mass data.
- From OpenStreetMap, we obtained the basic Distribution of Infrastructure in Juneau.
- From [6] we obtained the number of Juneau Cruise Passengers from 1998 to 2023 and the satisfaction level of Juneau residents with tourism in selected years.

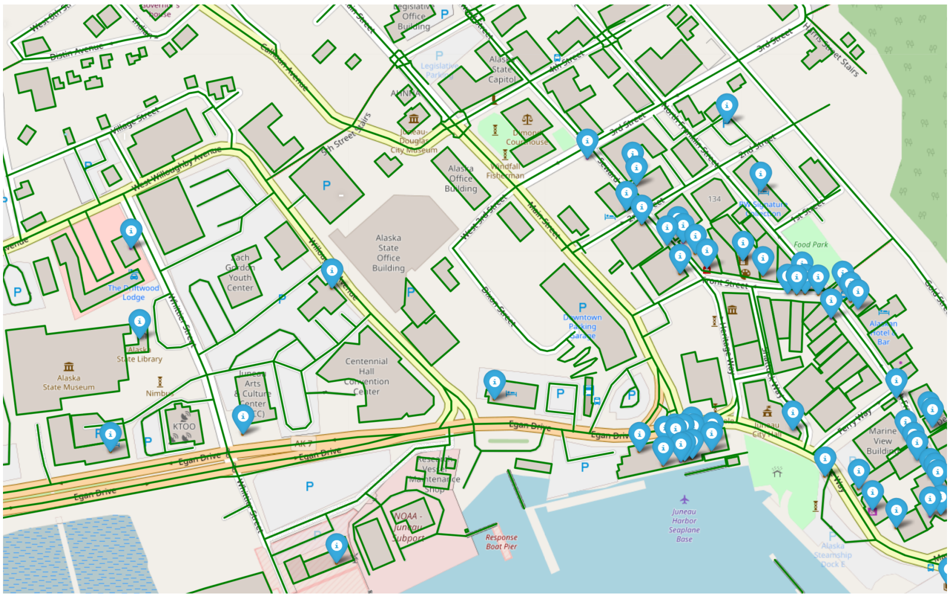

Figure 3: Distribution of Selected Infrastructure in the City of Juneau

4 Model Establishment

Sustainable tourism is a concept that encompasses the entire tourism industry and should address environmental issues such as infrastructure, carbon emissions and the preservation of tourist attractions, as well as factors such as economic prosperity, social harmony and so on.

4.1 Model Overview

The environmental sustainability indicator describes the combined impact of factors such as carbon footprint, pressure on infrastructure and life quality of local residents. We designed a sustainable tourism model based on the environmental sustainability indicator, taking into account economic principles such as demand model and a series of measures.

We will optimize long-term revenue and sustainability indicator, with tax caps, environmental capacity and infrastructure capacity as constraints. In addition, our decision variables include passenger number caps, carbon footprint tax rates and infrastructure tax rates.

The basic steps of the sustainable tourism model are as follows:

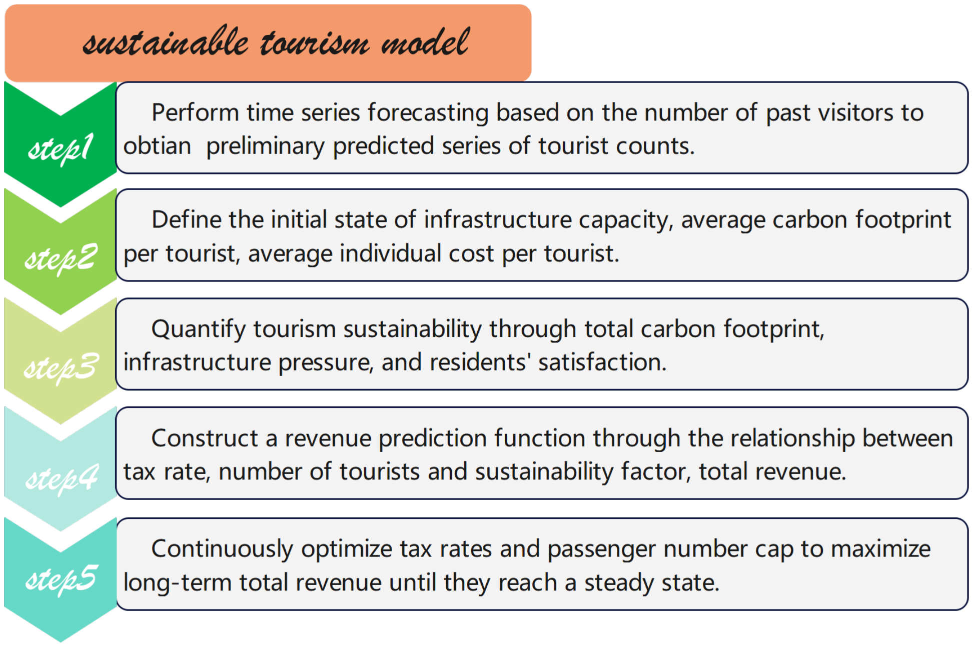

Figure 4: Model Overview

4.2 Model I: Passenger Number Prediction Model

4.2.1 Autoregressive Prediction Model

The number of passengers in the target city in the t-th year is denoted as N_t. First, the number of passengers over the past 20 years is shown in the figure. It can be seen that passenger volume time series data have significant trends. the ARIMA model can eliminate trends through difference (parameter $d = 1$) and capture the dynamic behavior of the data through autoregression (parameter p) and sliding averages (parameter $q = 0$)., thus we apply the ARIMA(p,d,0) model to the passengers count time series data. The general form of the model is as follows:

$$\Delta^{(d)} N_t = \sum_{j=1}^{p} a_j \Delta^{(d)} N_{t-j} + \epsilon_t \tag{1}$$

where $\Delta^{(d)}$ denotes the d-th order differencing operator. $\epsilon_t \sim N(0, \varepsilon_t^2)$ represents the residual of the model. Therefore, the predicted value of the tourist count after t years, under first-order differencing, can be expressed as:

$$\hat{N}_t = \sum_{j=1}^{p} a_j \mathbb{E}(\Delta N_{t-j}) + \hat{N}_{t-1} \tag{2}$$

In this way, we obtain the preliminary predicted series of tourist counts using the ARIMA model, denoted as N_t^0.

4.2.2 Double-Log Demand Adjustment Model

After obtaining the preliminary forecast of passenger numbers N_t^0 using the ARIMA model, we apply a Double-log demand model to adjust the predictions. We introduce the average individual cost $Cost$ as well as the carbon footprint tax rates $a_{1,t}$ and infrastructure tax rates $a_{2,t}$, which will be fed back to support the sustainable development of the tourism industry in the following. The average individual cost $Cost$ can be obtained from a linear regression of total revenue and the number of tourists over time.

The Double-log demand elasticity describes the relationship between the number of tourists and consumption. The basic principle is that:

$$\ln\left(\frac{N_t}{\mathbb{E}(N_t)}\right) = E_p \ln\left(\frac{P_t}{\mathbb{E}(P_t)}\right) \tag{3}$$

where N_t is the actual number of passengers in the t-th year, $\mathbb{E}(N_t)$ is the expected number of tourists, P_t is the actual price, and $\mathbb{E}(P_t)$ is the expected price. E_p represents the price elasticity of demand.Here we have $P_t = (1 + \epsilon_t + a_{i,t} + a_{2,t})Cost$ and $\mathbb{E}(P_t) = Cost$, ϵ_t is Gaussian white noise. Using this elasticity relationship, we obtain the adjusted passenger numbers prediction:

$$N_t^1 = (1 + \epsilon_t + a_{1,t} + a_{2,t})^{E_p} N_t^0 \tag{4}$$

This adjusted prediction N_t^1 takes into account the effect of the carbon footprint tax and the infrastructure tax on the demand for tourism, offering a more accurate forecast of passenger numbers in light of changing policies and external factors.

4.2.3 Sustainability Revision Model

We introduce a sustainability indicator S_t, which will be detailed later. It measures the sustainability of tourism in the target city at year t. A higher value of S_t indicates a more sustainable tourism system. To incorporate sustainability, we introduce the function $D(S_t)$, which reflects how the sustainability indicator influences the number of tourists. The adjusted prediction of the number of passengers for the t-th year is:

$$N_t^2 = D(S_{t-1}) \cdot N_t^1 \tag{5}$$

Based on the literatures, we define the adjustment function as:

$$D(S_t) = \gamma_1 \arctan(\gamma_2 S_t) \tag{6}$$

where γ_1 is the adjustment sensitivity factor and γ_2 is the responsiveness factor. 5 shows that the current year's tourism demand is influenced by the previous year's sustainability indicator. Specifically, when the environment has been severely damaged in the previous year, S_{t-1} will be low, leading to a significant reduction in tourism numbers in the current year.

To account for capacity limits, we introduce a maximum passenger number M. The final predicted number of passengers for the current year is:

$$N_t = \min\left(N_t^2, M\right)$$

This ensures that the final number of passengers respects both sustainability goals and the city's capacity constraints, with the impact of sustainability from the previous year reflected in the adjusted prediction.

4.3 Model II: Sustainability indicator model

In order to determine the level of sustainability of tourism development, we developed a sustainability indicator evaluation model with total carbon footprint, infrastructure pressure and local residents' satisfaction as evaluation criteria. The modeling idea is as follows:

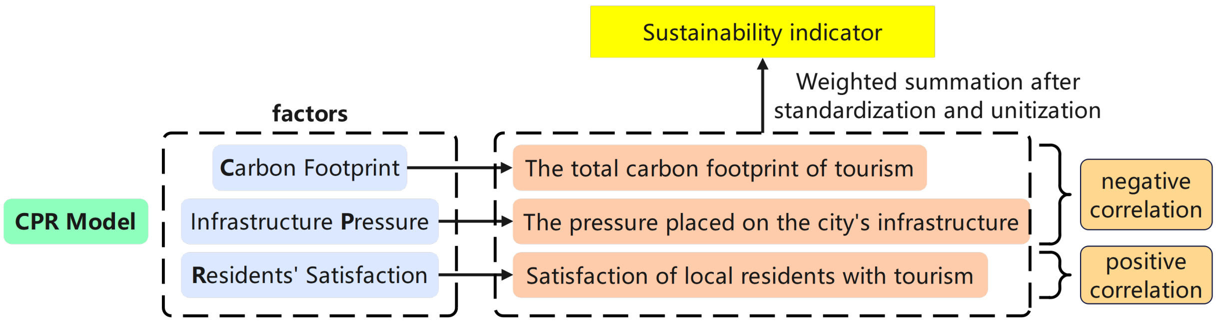

Figure 5: Caption

4.3.1 Total Carbon Footprint

The total carbon footprint of tourism is a key indicator of the environmental sustainability of tourism development in the target city. In this model, we calculate the total carbon footprint in year t, denoted as C_t, as the product of two factors: the average carbon footprint per tourist, $\bar{c}$, and the total number of tourists in that year, N_t. Mathematically, this relationship is expressed as:

$$C_t = \bar{c} \cdot N_t \tag{7}$$

where $\bar{c}$ is the average carbon footprint per tourist, and N_t is the total number of tourists in year t. To mitigate the carbon footprint, we assume that the income generated from the carbon footprint tax, $a_{1,t}$, is reinvested into carbon footprint reduction efforts for the following year. Specifically, the total carbon footprint in year $t+1$, denoted as C_{t+1}, is adjusted by the mitigation efforts as follows:

$$C_{t+1} = \bar{c} \cdot N_{t+1} - k_1 \cdot a_{1,t} \cdot \text{Cost} \cdot N_t \tag{8}$$

where k_1 is a constant representing the efficiency of carbon footprint mitigation,This equation reflects how the additional revenue generated from the carbon footprint tax is used to reduce the total carbon footprint in the following year.

4.3.2 Infrastructure Pressure

Another critical factor in evaluating the sustainability of tourism development is the pressure placed on the city's infrastructure. The infrastructure pressure in year t, denoted as Q_t, is calculated as the ratio of the total number of tourists N_t to the infrastructure capacity I_t in that year. This relationship is expressed as:

$$Q_t = \frac{N_t}{I_t} \tag{9}$$

where I_t represents the infrastructure capacity in the same year. A higher value of Q_t indicates greater strain on the infrastructure, which can negatively impact the sustainability of tourism in the city.

To ensure that infrastructure capacity keeps pace with tourism growth, we assume that additional income generated from the infrastructure tax, $a_{2,t}$, is reinvested in infrastructure development. Specifically, we have the following formula:

$$I_{t+1} = I_t + k_1 \cdot a_{2,t} \cdot \text{Cost} \cdot N_t \tag{10}$$

where k_1 is a constant representing the efficiency of reinvestment. By modeling this relationship, We can better assess how we can take measures to feed back into the system with additional revenue to promote sustainable tourism.

4.3.3 Residents' Satisfaction

Residents' satisfaction is another important factor in evaluating the sustainability of tourism development. In year t, the level of residents' satisfaction, denoted as R_t, reflects how local residents perceive the impact of tourism on their lives. We have collected survey results???fig from past studies to categorize residents' attitudes toward tourism. The survey includes options such as "Positive outweighs negative," "Neutral," and "Negative outweighs positive." Based on these responses, we aim to model how residents' satisfaction is influenced by both the number of tourists and the total revenue generated by tourism.

To quantify residents'satisfaction, we use a model that incorporates both the total number of tourists N_t and the total tourism revenue R_t. Since the relationship between these variables and satisfaction is complex, we adopt **random forest method** .The algorithm builds multiple decision trees, where each tree makes a prediction based on random subsets of the data and features. The final prediction is made by averaging the predictions from all the individual trees, making the model more resilient to overfitting and capable of capturing complex interactions between variables???liucheng fig.

In our model, we express the residents' satisfaction indicator R_t as a function of the number of passengers N_t and total revenue T_t, represented as:

$$R_t = \sigma(N_t, T_t) \tag{11}$$

where $\sigma(N_t, R_t)$ represents the satisfaction function, which is learned through a random forest model. By training the model on historical data about passenger numbers, total revenue and residents' attitudes, we can predict the level of residents' satisfaction in each year based on the corresponding passenger numbers and revenue.

To obtain the final sustainability indicator S_t, we weighted the above three factors after normalizing and unitizing them. At this point, as the sustainability indicator S increases, the corresponding tourism sustainability increases

5 Model computed and Result Analysis

5.1 Optimisation of tourism industry in Juneau, Alaska

5.1.1 Algorithm of the Model

Our model performs calculations in a differential form, with the results of each calculation derived from the previous one, to simulate development of tourism revenues in the city of Juneau over time and finding the best measures to stabilise the tourism industry.

Algorithm 1 Revenue Prediction Simulation

Input:

Maximum number of passengers M

Tax revenue spent on natural environment $a_{1,t}$

Tax revenue spent on infrastructure maintenance $a_{2,t}$

The maximum forecast years $PreTime$

Output:

Total revenue within the subsequent $PreTime$ years T

Annual revenue within the subsequent $PreTime$ years T_t

Number of annual passengers N_t

function Passenger(M , $a_{1,t}$, $a_{2,t}$, PreTime)
for $t = 1 , \dots , PreTime$ **do**
  // Calculation of Revenue R_t:
  $P_t \leftarrow (1 + \epsilon_t + a_{1,t} + a_{2,t}) \cdot Cost;$
  $N_t^0 \leftarrow N_{t-1} \cdot P_t^{Ep};$
  $N_t \leftarrow \min\{M , r_1 \arctan(r_2 S_{t-1}) \cdot N_t^0\};$
  $T_t \leftarrow P_t N_t - a_{1,t} Cost \cdot N_t - a_{2,t} Cost \cdot N_t;$
  // Calculation of Sustainability indicator S_t:
  $C_t \leftarrow \bar{c} \cdot N_1 - k_1 \cdot a_{1,t-1} Cost \cdot N_{t-1};$
  $I_t \leftarrow I_{t-1} + k_2 \cdot a_{2,t-1} Cost \cdot N_{t-1};$
  $R_t \leftarrow \sigma(N_t, T_t);$
  $Q_t \leftarrow \frac{N_t}{I_t}$
  $S_t \leftarrow \lambda_1 \cdot C_t + \lambda_2 \cdot Q_t + \lambda_3 \cdot R_t;$
end for
end function

Particle Swarm Optimization (PSO) is an evolutionary computation technique inspired by the social behavior of bird flocks or fish schools[7]. It is widely used to optimize continuous and discrete functions. In this model, PSO is employed to optimize the parameters $a_{1,t}$ and $a_{2,t}$ to maximize the sustainability indicator S_t while maintaining economic stability. PSO is particularly suitable for this task because of its simplicity, ability to converge quickly to a near-optimal solution, and effectiveness in handling non-linear, multi-dimensional optimization problems.

Algorithm 2 General Particle Swarm Optimization (PSO) Algorithm

Input:

Objective function $f(x)$
Number of particles n
Maximum number of iterations $Iter_{max}$
Inertia weight w, cognitive coefficient c_1, social coefficient c_2

Output:

Optimal solution x^*

Initialize the position x_i and velocity v_i of each particle randomly
Evaluate the fitness $f(x_i)$ for each particle
Set the personal best position $p_i \leftarrow x_i$ and global best position $g \leftarrow \arg\max f(x_i)$
for $t = 1, \ldots, Iter_{max}$ **do**
  for each particle i **do**
    Update velocity: $v_i \leftarrow w \cdot v_i + c_1 \cdot r_1 \cdot (p_i - x_i) + c_2 \cdot r_2 \cdot (g - x_i)$
    Update position: $x_i \leftarrow x_i + v_i$
    Evaluate the fitness $f(x_i)$
    if $f(x_i) > f(p_i)$ **then**
      Update personal best: $p_i \leftarrow x_i$
    end if
  end for
  Update global best: $g \leftarrow \arg\max f(p_i)$
end for
return g

5.1.2 Model Parameter Settings

First, all the formulas in the model will be shown below:

$$\begin{cases} N_t = \min\{\gamma_1 \arctan(\gamma_2 S_{t-1}) \cdot (1 + \epsilon_t + a_{1,t} + a_{2,t})^{Ep} N_t^0, M\} \\ S_t = \lambda_1 \cdot C_t + \lambda_2 \cdot N_t / I_t + \lambda \cdot R_t \\ C_t = \bar{c} \cdot N_t - k_1 \cdot a_{1,t-1} Cost \cdot N_{t-1} \\ I_t = I_{t-1} + k_2 \cdot a_{1,t-1} Cost \cdot N_{t-1} \\ R_t = \sigma(N_t, T_t) \end{cases} \tag{12}$$

Using Juneau's data as a reference,we set some of the parameters in the model to appropriate values and adjusted them to see how the model performs with different parameters. Eventually, we determined the model parameters to the following values and used the model to solve the results.

It is worth noting that our model is highly adaptive and does not apply only to the Juneau city. When the model is migrated to other regions, local data are needed to support it.

Table 3: Parameter Settings

Parameter	Value	Parameter	Value
$Cost$	446.94	E_p	-1
$\bar{c}$	14.4	$\bar{I}$	1
γ_1	0.64	γ_2	1e-4
k_1	100	k_2	100
λ_1	0.8	λ_2	0.1
λ_3	0.1	I_0	1e+5

5.1.3 Result of the Simulation

We simulated the tourism development in Juneau and found the most sustainable approach,The maximum number of passengers per year in our plan is 1.85 million ,and the tax rate in the optimized plan is shown in Figure6.

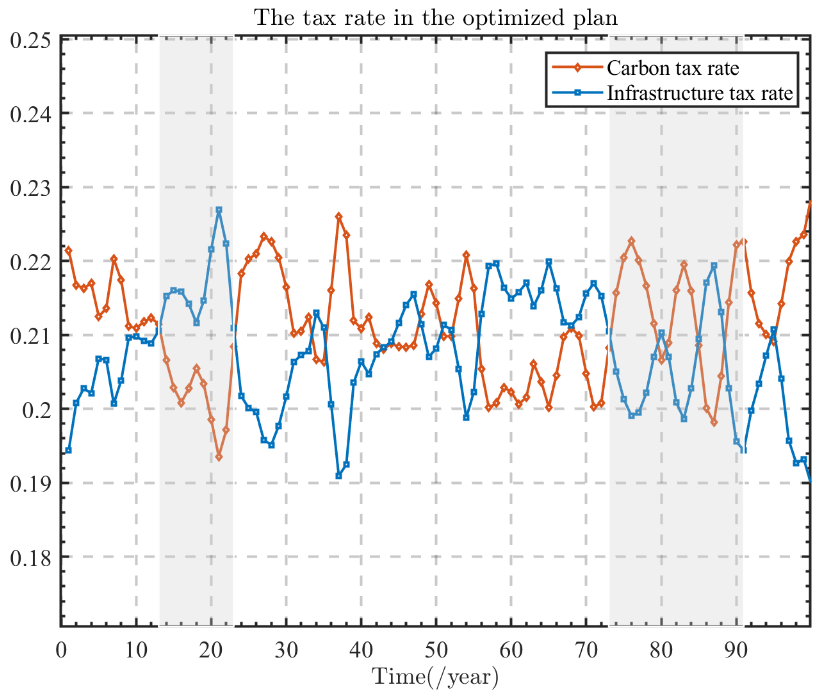

Figure 6: The tax rate in the optimized plan

To reflect the impact of our sustainable planning, we set up a control group that does not implement any measures for managing tourism. The results, including the total annual revenue and environmental sustainability indicators for both the control group and our optimized plan, are shown in the figure below.

We can obtain that:

- Based on Figure7,Although the total revenue without taking measures is higher in the first 20 years compared to the scenario where measures are implemented, the overall revenue without sustainable tourism planning gradually declines over time. By the 21st year, it falls below the revenue of the sustainable scenario, and by the 82nd year, it even reaches zero. In contrast, the scenario with sustainable planning maintains overall stability for a much longer period.

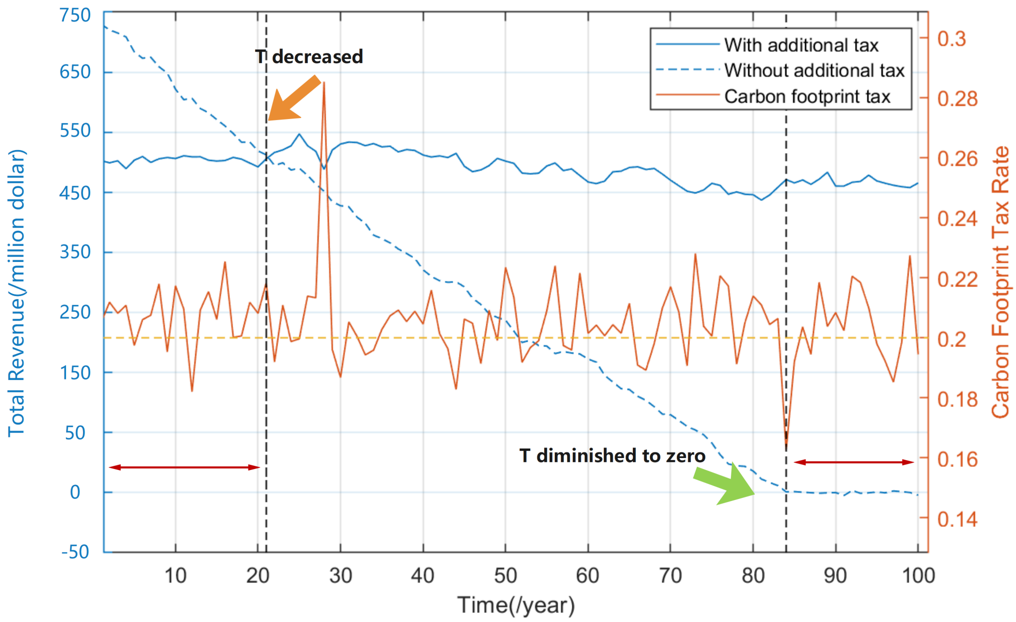

Figure 7: The total revenue of the optimized and control group

- The carbon footprint tax peaks in the 28th year, which is due to the higher total revenue and number of tourists in the previous year. As a result, the additional tax rate is increased in the following year to control the number of tourists and maintain the sustainability of tourism. On the other hand, the additional tax rate reaches its lowest point in the 83rd year, as the total revenue and number of tourists in the previous year are relatively low. Consequently, the tax rate is reduced in the following year to attract more tourists,This reflects the self-regulating capability of our model to foster the development of a more sustainable tourism industry.

- Based on Figure8, on the left side we can see that the overall sustainability indicators in the case of action are higher than those of the control group and remain overall stable for a considerable period of time, while the overall sustainability indicators in the case of no action show a decreasing trend. On the right hand side, we see that in 2060, the total revenue and the number of passengers in the experimental group are close to those of the control group, but the pressure on the infrastructure is alleviated to some extent, while the sustainability indicator is significantly higher than that of the control group, reflecting that our scenario of allocating additional tax revenue to sustainability protection has significant benefits in the long run.

To quantify the advantages, we define an optimization rate formula:

$$K = \frac{k_{\text{before}}}{k_{\text{after}}} - 1 \tag{13}$$

where k_{before} represents the metrics before optimization and k_{after} represents the metrics after optimization. $k_{\text{before}} \geq k_{\text{after}}$. From the experimental data We found that the optimization rate of the total annual revenue for the first 50 years is 6.9%, while for the first 100 years, the optimization rate reaches 73%. This clearly demonstrates

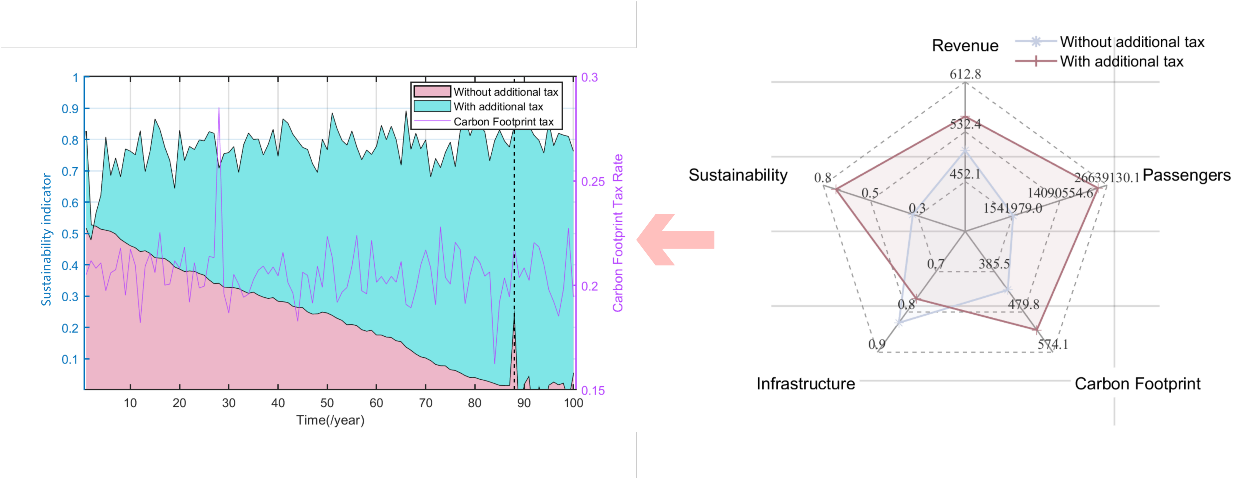

Figure 8: Sustainability indicator (left) and the various factors for the year 2060 (right) of the optimized and control group

the advantages of our model in promoting the long-term development of the tourism industry.

The simulation results of the model give us the **answer to question 1**:

- We ensure the sustainable development of the tourism industry by **adopting measures** to limit the number of tourists per year to a maximum of 1.85 million, as well as the collection of additional revenues such as the carbon footprint tax and infrastructure tax at an average rate of 0.2. The **direct optimising factor** of our model is the overall revenue in the next hundred years, while the sustainability indicators have a significant impact on the revenue in the long run, so the total carbon footprint, infrastructure pressure, etc., and sustainability indicators are all are **indirect optimisers**, while the cap on the levy of the additional tax rate, and the cap on the total number of tourists per year are **limiting factors**.

- By investing the additional revenue from the carbon footprint tax and infrastructure tax into the maintenance of the corresponding areas in the second year, it is clear from the above analysis that **these expenditures can alleviate the pressure on infrastructure in the long run and maintain the stability of the sustainability indicators of the tourism industry, thus further guaranteeing the stability of the revenue in the long run**. In the specific case of Juneau, because of the importance of Juneau's glacier attractions to the local tourism industry, the carbon footprint factor is more heavily weighted in the sustainability indicators, with the total carbon footprint and the corresponding carbon footprint tax rate being relatively **important factors**.

5.2 Optimisation of tourism industry in other districts

Compared to Juneau, Barcelona has a much larger population (about 50 times that of Juneau) on a much smaller land area (about 1/8 the size of Juneau), and thus it can be tentatively guessed that it has a severe infrastructure shortage. So, we picked Barcelona as another location affected by overtourism for our study. Similarly, we determined the model parameters to the following values using Barcelona's data as a reference and used the model to solve the results.

Table 4: Parameter Settings

Parameter	Value	Parameter	Value
$Cost$	601.23	E_p	-1
$\bar{c}$	14.4	$\bar{I}$	1
γ_1	0.64	γ_2	1e-4
k_1	100	k_2	100
λ_1	0.1	λ_2	0.8
λ_2	0.1	I_0	1e+4

We simulated the tourism development in Barcelona and found the most sustainable approach,The maximum number of passengers per year in our plan is 1.94 million, and the tax rate in the optimized plan is shown on the left of Figure9.In addition, we selected Chamdo, Tibet as a study location with fewer tourists, set the parameters accordingly, and optimised and simulated the plan,the result is shown on the right of Figure9 .

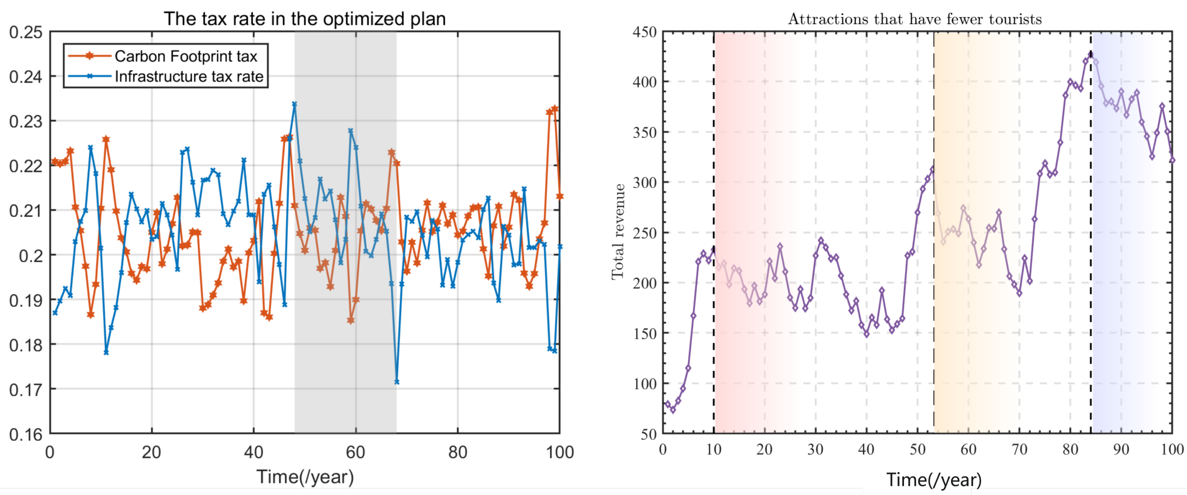

Figure 9: The tax plan in Barcelona (left) and the simulated total revenue in Chamdo, Tibet (right)

At this point, we can analyse the simulation results and answer question 2.

- When applying our model to study another location affected by over-tourism, we will **adjust the weights of the three factors in the sustainability indicator according to the local situation**, for example, if the local tourism industry is affected by a higher carbon footprint, e.g., with glaciers, etc. as the main attraction, the weight of the corresponding factor will be increased, and if the local infrastructure is poorly developed, the weight of the pressure on the infrastructure will be increased, and, **in addition, the total amount of infrastructure, the per capita carbon footprint, and other parameters will also be fitted according to local conditions**. Taking Barcelona as an example, the tourism industry in Barcelona is dominated by local churches, cultural parks, etc., and has a Mediterranean climate, which is less affected by the carbon footprint factor, so the corresponding weights are lower. From the left of Figure9, it can be seen that the overall carbon footprint tax rate is lower than that of the scenario for the city of Juneau, **so the**

pressure on the infrastructure and the satisfaction of the residents are more important factors, and measures such as the collection of additional infrastructure tax are the most important accordingly.

- When the study site has fewer tourists, we first take the measure of collecting lower or no tax, and do not limit the maximum number of tourists per year, so that more tourists come to the site, when the number of tourists rises to a certain number, the sustainability of the local environment will be undermined to a certain extent, therefore, **we will collect a certain amount of additional tax for the protection of sustainability, but also to maintain the number of tourists per year is relatively stable, After a certain period of time, the sustainability indicators such as pressure on the local infrastructure have been eased, at which point we will continue to reduce the tax rate or not collect any tax to attract more tourists**. As shown on he right of Figure9, under our scenario, from year 10 to year 50, the optimisation of total revenue K reached 34%, while from year 50 to year 84, the optimisation of the total revenue was 38%.The overall change in total revenue over time follows an 'S' shaped trend, which is a **cyclical process of 'low tax growth - stable tax collection - low tax growth'**.

6 Model Evaluation and Discussion

6.1 Sensitivity Analysis

In this paper, we have developed two models:the Passenger Numbers Prediction Model and the Sustainability indicator model. In our models, there are many parameters that need to be given artificially, and most of them have been given suitable values through simulation. However, there are still some parameters that may change in real situations. For example, the price white noise coefficient ϵ and infrastructure capacity per capita $\bar{I}$ may fluctuate within a small range due to environmental and stochastic factors, so we vary ϵ and $\bar{I}$ respectively, leaving the other parameters unchanged, and re-simulate the optimised model in **Sec5.1** to observe the model's calculations.

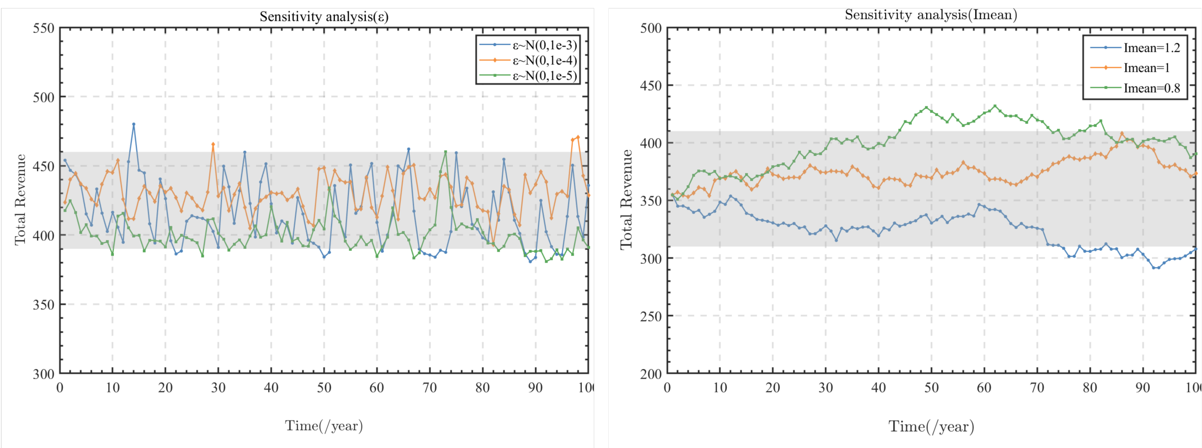

Figure 10: Sensitivity Analysis of ϵ and $\bar{I}$

The variance of ϵ was firstly set to $1e-3$, $1e-4$ and $1e-5$ to simulate the fluctuation of the price coefficient; then $\bar{I}$ was adjusted to 0.8, 1 and 1.2 to simulate the fluctuation of per capita infrastructural capacity in response to the environmental changes, and the change of total revenue of the optimal tourism management scheme was observed. **The results show that when ϵ and $\bar{I}$ fluctuate within a certain range, the predicted total revenues in the next 100 years do not change much, and the trends are basically the same, which indicates that the stability of the model is good.**

6.2 Strengths and Weaknesses

6.2.1 Strengths

- We develop a Passenger Number Prediction Model with a sustainability factor that takes into account the impact of environmental capacity and infrastructure capacity on long-term revenues, and avoid the confusion of conflicting optimization goals by establishing the relationship between the two and running a single-objective planning algorithm, as opposed to the usual multi-objective planning. Meanwhile, since it is difficult to harmonize the sustainability factor with the income measure, the Passenger Number Prediction Model associated with the sustainability factor solves the complexity of setting the weights.
- We take into account the impact of multiple factors (tax rates, environment, infrastructure, etc.) on visitor numbers, which helps the model to be applicable in different regions. For example, the model performs extremely well in regions with relatively fragile natural environments (glaciers, rivers, etc.) as well as in regions with relatively stressful infrastructures (densely populated, economically disadvantaged, etc.). Even in less-tourism regions, our model can still help the region to develop tourism rapidly and sustainably.
- Adopting multi-dimensional indicators to assess the sustainability of tourism, we use the total carbon footprint, infrastructure pressure and residents' satisfaction to assess the sustainability of tourism, which covers natural, social and economic aspects, and can reflect the development of tourism in a more comprehensive way.
- The parameter indicators of the model are determined by reviewing relevant literature and a large number of experiments. Our model indicators are not given arbitrarily, but are more accurate calculation parameters based on relevant data and simulation experiments, which makes the model more stable and accurate.

6.2.2 Weaknesses

- When considering resident satisfaction, due to space and data constraints, we only consider satisfaction as a function of total revenue and the number of tourists,in fact resident satisfaction may be affected by a variety of other factors.
- Due to some objective reasons, we could not obtain all the data needed. Therefore some initial values for the model were estimated based on government reports, which may have some tiny errors.

6.3 Conclusion

Sustainable tourism is a complex issue that encompasses environmental, economic and social aspects. With a series of realities such as global warming and melting glaciers, it is worthwhile for us to think seriously about how to protect our homeland while generating sufficient income for the local community. We hope that our model can provide some help for sustainable tourism development, and we also hope that readers can give us some suggestions to improve our model!

7 Memorandum

To: The Tourist Council of Juneau
From: Team # 2520009
Date: January 27, 2025
Subject: Sustainable Tourism Strategies for Juneau

Dear Members of the Tourist Council,

To ensure the long-term sustainability of Juneau's tourism industry, we propose a series of strategic measures based on our comprehensive analysis. These measures are designed to address key areas such as environmental protection, community engagement, economic diversification, and technological innovation. By implementing these strategies, Juneau can position itself as a leader in sustainable tourism, safeguarding its unique environment and economic prosperity for future generations.

We suggest **limiting annual tourists** to **1.85 million annually** to preserve infrastructure and natural assets, particularly glaciers. Additionally, we recommend **implementing dual taxes**: a **carbon footprint tax** and an **infrastructure tax** at an average rate of **0.2** to generate revenue and incentivize eco-friendly practices. The tax revenues should be **reinvested** to maintain infrastructure, offset carbon emissions, and support glacier preservation projects, ensuring steady long-term growth.

By **reinvesting additional tax revenues** into critical areas, we can mitigate infrastructure strain and ensure steady tourist inflows. This approach fosters consistent economic growth and long-term prosperity. **Environmental protection** measures will address the carbon footprint and sustain Juneau's iconic attractions, particularly its glaciers, aligning with global sustainability goals and preserving the city's competitive advantage in ecotourism. **Sustainable development** can be achieved by managing tourist numbers and improving infrastructure, securing the resilience and sustainability of the tourism industry for the next century, protecting both the environment and the local community.

We propose to regularly review the effectiveness of these measures through key performance indicators, such as infrastructure usage, carbon emissions, and tourist satisfaction ratings. Policies should be adapted as necessary to address unforeseen challenges or to capitalize on emerging opportunities, ensuring continued alignment with Juneau's economic and environmental goals.

By adopting these carefully crafted strategies, Juneau can position itself as a pioneering leader in sustainable tourism. This forward-thinking approach will not only safeguard the region's unique and pristine environment but also ensure economic prosperity for current and future generations.

Best wishes!

Sincerely,

Team # 2520009

References

[1] https://www.thetravelfoundation.org.uk/invisible-burden/

[2] Elkington J. Partnerships from cannibals with forks: The triple bottom line of 21st-century business[J]. Environmental quality management, 1998, 8(1): 37-51.

[3] Goel P. Triple Bottom Line Reporting: An Analytical Approach for Corporate Sustainability[J]. Journal of Finance, Accounting & Management, 2010, 1(1).

[4] Sato K. Additive utility functions with double-log consumer demand functions[J]. Journal of Political Economy, 1972, 80(1): 102-124.

[5] Moldan B, JanouÅąkovÃą S, HÃąk T. How to understand and measure environmental sustainability: Indicators and targets[J]. Ecological indicators, 2012, 17: 4-13.

[6] https://juneau.org/wp-content/uploads/2024/02/Juneau-Visitor-Circulator-Study-Final-Report-2024-1.pdf

[7] Marini F, Walczak B. Particle swarm optimization (PSO). A tutorial[J]. Chemometrics and Intelligent Laboratory Systems, 2015, 149: 153-165.