

The MCM Thesis of Team 2521799

Summary

This article develops an integrated mathematical framework to determine optimal tourism carrying capacity through multi-criteria assessment of environmental thresholds, infrastructure adequacy, and community receptivity metrics, supplemented by other critical socioeconomic indicators. The policy-oriented model provides data-driven decision support for the City and Borough of Juneau government to systematically address over-tourism challenges while advancing sustainable tourism governance through balanced resource allocation.

Our approach consists of five models:

- **Supply-demand analysis** provides a method by using past data to establish a system of equations to predict the supply-demand relationship in Alaska's tourism industry, through which we successfully solved the relationship between the number of tourists and local fiscal revenue, paving a solid foundation for deeper analysis.
- **negative externalities quantification** quantitatively analyzed the impact of tourist numbers on the economy, environment, and society, which are three main topics of sustainable economy. We quantified the negative environmental effects of tourism as economic losses, ultimately deriving the relationship between net economic benefits with fiscal revenue.
- **Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model** provides a robust econometric specification for the decomposition of the drivers of anthropogenic emissions, particularly through the tourism-environment nexus.
- **Dynamic analysis and optimization** transforms prior fiscal surpluses into tourism infrastructure capital to boost regional tourism carrying capacity. By constraining annual tourist numbers below updated capacity thresholds, it determines optimal intertemporal investment ratios that maximize aggregate social welfare (economic gains and resident satisfaction) over time.
- **Panel Cross-Sectional Dependence (CD) Model** quantifies systemic inter-dependencies through multidimensional indicators including tourism intensity, economic development trajectories, CO emission patterns, and primary energy utilization rates across urban systems. This econometric framework reveals latent covariance structures in cultural proximity, technological spillovers, and economic convergence mechanisms, thereby establishing transferable policy benchmarks for municipalities confronting over-tourism dilemmas.

Keywords: Supply-demand analysis, Differential Evolution(DE), externalities quantification, Dynamic analysis, Cross-sectional Dependence (CD) tests, sustainable tourism

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1 Introduction

Sustainable development has emerged as a pivotal concern in contemporary tourism planning and management (Victor T.C. Middleton et al., 1998)[1]. As a multidimensional concept, sustainable tourism necessitates the balanced integration of economic viability, environmental preservation, social equity, and cultural continuity. The tourism industry's complex ecosystem - comprising core components such as transportation networks, aviation systems, and hospitality infrastructure - has been identified as a significant contributor to escalating energy consumption patterns (Victor T.C. Middleton et al., 1998)[2]. This phenomenon is further exacerbated by ancillary economic activities associated with tourism development (Udemba et al., 2019)[3].

The environmental ramifications of this energy-intensive paradigm manifest most acutely through increased carbon emissions. Empirical studies reveal that tourism-related CO_2 emissions surged from 3.9 to 4.5 gigatons between 2009 and 2013 [4], with the sector's expanded energy demands directly correlating with elevated levels of greenhouse gas (GHG) emissions (Udemba et al., 2019)[3]. These environmental impacts must be analyzed in conjunction with the industry's broader socioeconomic implications. The tripartite effects spanning social dynamics, economic structures, and ecological systems demand rigorous examination (Danish et al., 2018)[5], particularly as sustainable tourism development fundamentally depends on the conscientious preservation of natural habitats and cultural heritage. Juneau's tourism sector currently represents a 1.6 billion USD



Figure 1: splendid sight of Juneau

market value industry [6], yet faces critical sustainability challenges. Recent studies by the University of Alaska and local environmental monitoring reports reveal three pressing issues: accelerated glacial retreat, excessive carbon emissions, and unsustainable waste generation patterns (Travel Foundation et al., 2019)[7], [8]. These environmental stressors threaten to destabilize the region's tourism ecosystem, prompting urgent calls for sustainable development strategies.

Sustainable tourism in this context requires a balanced policy framework that op-

timizes positive economic impacts while minimizing ecological degradation. Current research emphasizes the need to establish clear interconnections between four core elements[9]:

- sustainable tourism practices
- environmental conservation metrics
- economic growth patterns
- energy consumption profiles

This multidimensional analysis should further incorporate socioeconomic variables including local community engagement, tourism revenue distribution, and workforce development indicators.

Such comprehensive assessment would enable policymakers to develop targeted interventions addressing both immediate environmental concerns and long-term economic viability. Particular emphasis should be placed on quantifying the feedback mechanisms between glacial preservation efforts and tourism infrastructure planning, given the region's unique geographical characteristics.

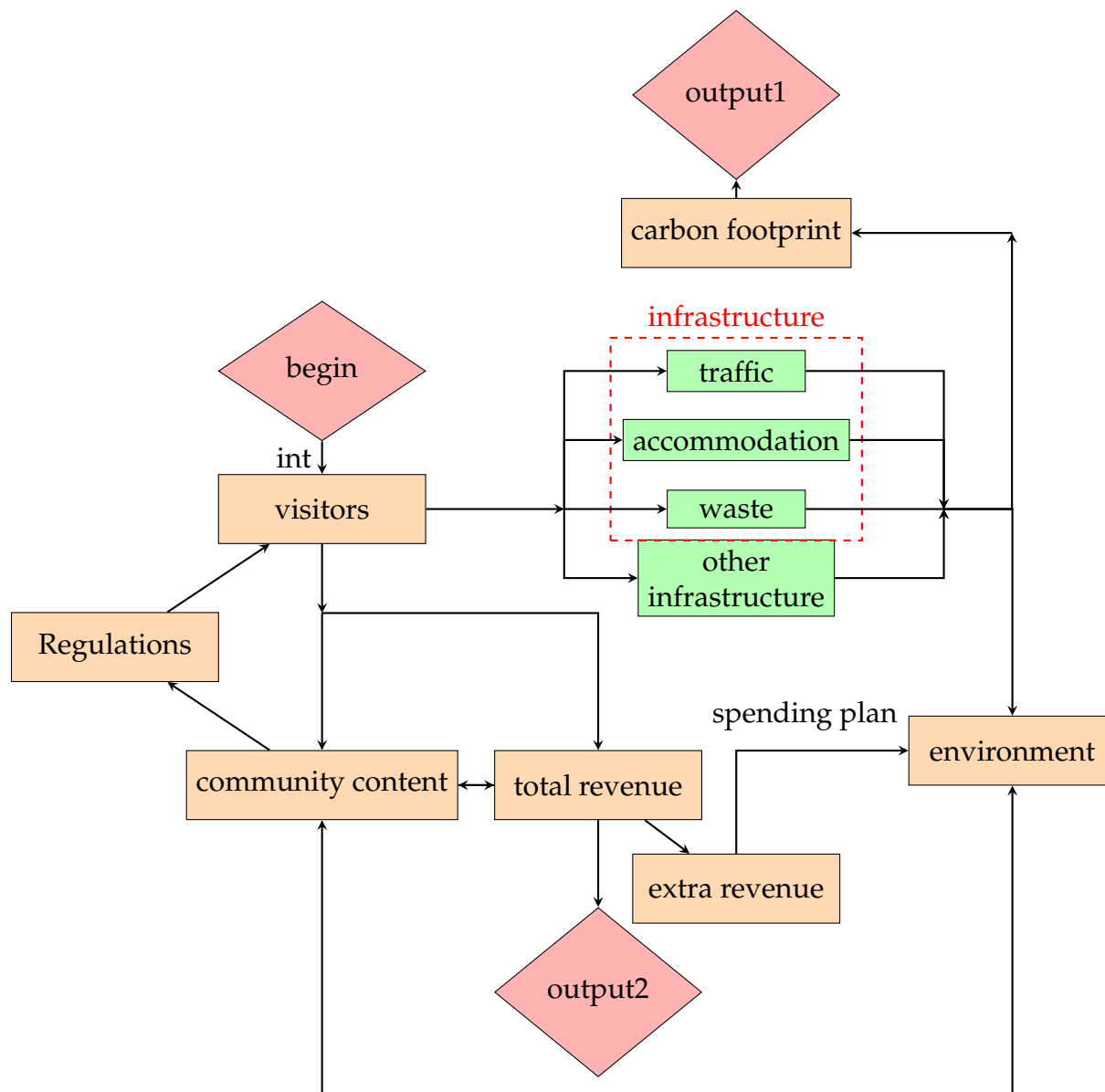
1.1 Assumptions

There are assumptions.

- In the short term, the tourism supply curve in Juneau City remains unchanged
- In the short term, the slope of tourism demand curve in Juneau City remains unchanged
- Stable indicators are remain unchanged with time goes by.They are the cost of water supply and electricity, the cost of garbage process, CO production per capita, etc.

Our Work

To clarify the process of our work, the process will be represented by the flow chart below:



Throughout the process of formulating policies to regulate the volume of incoming tourists, it is essential to consider various interactive relationships and competing interests simultaneously. The model we have developed incorporates a range of indicators that assist the Juneau government in addressing this complex, multi-objective, multi-criteria, and multidimensional challenge of imposing tourism restrictions.

In this context, traditional evaluation methods that rely on monetary values—such as cost-benefit analysis—often prove inadequate and unsuccessful (Douissa and Jabeur, 2020). To overcome these limitations, several techniques have been explored to support decision-making in tourism policy planning and implementation. These include the construction of synthetic indicators (Blancas et al., 2010), theoretical modeling (e.g., Evolutionary game theory; Blanco et al., 2009), and Multidimensional Analysis (Carrillo and Jorge, 2017).

2 Notations

The description of symbols to be used in the article are shown below:

Table 1: Symbols

Symbols	Discriptions
N^i	number of tourists in year i
TR^n	total revenue at year n
β	the weight of tourists' revenue in total revenue
TR_p^n	the public's revenue at year n
TR_g^n	the government's revenue at year n
p_n	the average tourist's consumption at year n
r_n	the proportion of tourists' rental expenses to their total consumption at year n
t_n	the average for consumption tax and rental tax
t_c	the average consumption tax of tourists at year 2022-2024
t_a	the average accommodation tax of tourists at year 2022-2024
a	the slope of supply curve to be sought by data
b	the intercept of supply curve to be sought by data
a_n	the slope of demand curve at year n to be sought by data and we assume that all of them are the same value a_0
b_n	the intercept of demand curve at year n to be sought by data
P_{ed}	the number of premature deaths (in ten thousands) from all causes under the current level of air pollution
t	the average loss of life years due to premature deaths from all causes caused by air pollution
G	the per capita GDP in the base year
α^j	the growth rate of per capita GDP in year j
r	the social discount rate
Pe^j	the exposed population in year j
RR^j	the relative risk attributable ratio for all-cause mortality caused by air pollution in year j
$C^j(\mu\text{g}/\text{m}^3)$	the concentration of PM2.5 in the air in year j
C_0	the PM2.5 health threshold provided by WHO
β	0.025723(according to WHO), the dose-response relationship between PM2.5 and non-accidental all-cause mortality
P_{eh}^j	the number of hospital admissions due to diseases associated with air pollution in year j

Table 2: Symbols

Symbols	Discriptions
n	air pollution-related diseases, including respiratory diseases and cardiovascular diseases
f_p^j	the number of hospital admissions under the current level of air pollution in year j
f_i^j	the the total number of hospital admissions under the current level of air pollution in year j
β_i	the regression coefficient, indicating the change in health risk i caused by a unit change in pollutant concentration
δ_c^j	the difference between the actual pollutant concentration in year j and the threshold concentration for health risks
C_n	the cost of hospitalization, including direct hospitalization costs and indirect costs such as transportation and nutrition for Juneau, it is about 4000 dollars
A^j	PM-2.5 caused by tourists activities in year j
T^j	PM-2.5 produced by transportation in year j
P_i	PM-2.5 produced by car of type i per mile
f_{1i}^j	the use frequency of cars of type i by tourists in year j
f_{2i}^j	the participation of activities of type i of tourists in year j
n_i^j	the average number of tourists using one car of type i in year j
$VTD^j(\text{km})$	the change of transportation currency caused by tourism in year j
VTD_i^j	the transportation currency in the ith month of year j
ATD_i^j	average PM-2.5 emission per capita in the activity of type i in year j
G_C^j	gross domestic product per capita in year j
$EM_{CO_2}^i$	total CO_2 emission in year i
$T_{CO_2}^i$	CO_2 emission from transportation of tourists in year i
$A_{CO_2}^i$	CO_2 emission from activities of tourists in year i
$P_{CO_2}^i$	CO_2 emission from planes in year i
$C_{CO_2}^i$	CO_2 emission from cruises in year i
$P_{aCO_2}^i$	average CO_2 emission per person from planes
ACM	average CO_2 emission per person from cruises
APD_i	average distance of the flight/sailing of the i type vehicle

Table 3: Symbols

Symbols	Discriptions
S_i	average CO_2 emission per mile for the plane of type i
W_i	average CO_2 emission per mile for the cruise of type i
n_{p_i}	average passenger capacity per plane(or cruise) of type i
x_i	the tourists population in Juneau in month i
y_i	the total CO_2 emission in Juneau in month i
K_{EM}	average total CO_2 emission per capita

3 Calculating and Simplifying the Model

3.1 Total revenue(TR)

Our function for total revenue in year n (a specific year) is based on the weight of tourists' revenue in total revenue, the public's revenue, and the government's revenue. The function is shown below.

$$TR^i = TR_p^i + TR_g^i. \quad (1)$$

To evaluate each parameter in this function, we take the steps shown below. We refer to data from the past three years to evaluate the specific value. The following shows what we have done to detect these values.

All i below is $\in \text{year}\{2022,2023,2024\}$

3.1.1 Evaluation for the average tax in the year 2022-2024

From official data, in the year 2022-2024, the consumption tax rate for Juneau is $t_c=5\%$ and the accommodation tax rate is $t_a=14\%$.

We assume that the proportion of the rental expenditures of tourists on their total spending in year n is r_n . Then we can get the average tax rate for these three years(2022-2024), that is:

$$t_i = t_c * (1 - r_i) + t_a * r_i. \quad (2)$$

3.1.2 Prediction for the supply and demand curve

We assume that the average tourist's consumption in year i is p_i . From the definition of tax rate, we can get the formulas below:

$$t_i = \frac{(a_i * N_i + b_i) - (a * N_i + b)}{a_i * N + b_i}, \quad (3)$$

where a_i and b_i represent the slope and the intercept of the demand curve at year n, a and b represent the slope and the intercept of the supply curve over these years, and N_i represents the total population of tourists in year i.

Meanwhile, we can obtain the average total consumption

$$p_i = a_i * N_i + b_i. \quad (4)$$

Our objection is to use the formulas above to get the value of a_i, b_i, a, b , where, according to our assumption, a_i is a fixed value, that is, it does not change with i . After solving the equation set above, we can get the supply and demand curve over the three years(2022-2024).

3.1.3 Evaluation for TR_p^i and TR_g^i

From the economic theory, we can obtain the balance production(represented by the tourist population) from the above results:

$$t_i = \frac{a_0 * N_i + b_i - a * N_i - b}{a_0 * N + b_i} \quad (5)$$

\Rightarrow

$$N = \frac{b_i - t_i * b_i - b}{a_0 * t_i - a_0 + a}. \quad (6)$$

because we can get t_i from data, N can be obtained by the above formula. Then TR_p^i and TR_g^i can be obtained according to all the values we have obtained above.

$$TR_p^i = N_i * (a * N_i + b), \quad (7)$$

$$TR_g^i = N_i * (a_0 * N_i + b_i - a * N_i - b). \quad (8)$$

With the formula(1) defined for TR, we can evaluate TR.

3.2 Economic loss caused by environmental reduction(EC)

3.2.1 Explanation for main factors

In accordance with Objective 1 establishing tourism performance as a revenue-based function, we propose quantifying environmental degradation through economic valuation to enable integrated assessment. The model incorporates three principal externalities: agricultural productivity loss, CO_2 emissions, and $PM_{2.5}$ pollution, with annual environmental cost denoted as EC^i . Notably, glacial retreat - while environmentally significant - is excluded from this framework due to its primary attribution to global climate systems rather than local tourism activities in Juneau. This selective parameterization aligns with our focus on direct anthropogenic impacts where tourism constitutes a measurable causal agent. The subsequent analysis systematically evaluates each identified factor through empirical modeling.

3.2.2 Production of PM-2.5

Assume that the health loss in year j is EC_{a1}^j . According to the related theory, we can obtain the following formula:

$$EC_{a1}^j = P_{ed}^j * G^j * \sum_{i=1}^t \frac{(1 + \alpha^j)^i}{(1 + r)^i}, \quad (9)$$

$$P_{ed}^j = [(RR^j - 1)/RR^j] * fp^j * Pe^j, \quad (10)$$

$$RR^j = [(C^j + 1)/(C_0 + 1)]^\beta. \quad (11)$$

Assume that the economic loss caused by hospitalization related to diseases caused by PM-2.5 in year j is EC_{a2}^j . According to the related theory, we can obtain the following formula:

$$EC_{a2}^j = P_{eh}^j * (C_n + G_C^j), \quad (12)$$

$$P_{eh}^j = \sum_{i=1}^n f_i^j \frac{\delta_c^j * \beta_i}{1 + \delta_c^j * \beta_i}. \quad (13)$$

These formulas can calculate the economic losses from premature death and relevant hospitalization caused by PM-2.5. The explanations for the above parameters can be seen in the parameter table. Most of them are fixed values that can be found from the previous data. However, t should be calculated by the gap between the average age of death caused by relevant diseases and the average age of natural death. In addition, δ_c^j should be calculated by real concentration (C^j) and because of the lack of data, we need to calculate it ourselves. Assume that the real PM-2.5 concentration consists of A^j (PM-2.5 caused by tourists activities) and T^j (PM-2.5 produced by transportation). The following formulas can give evaluations for them.

$$A^j = \sum_{i=1}^n f_{2i}^j * N_j * ATD_i^j, \quad (14)$$

$$T^j = \sum_{i=1}^n P_i * \frac{f_{1i}^j}{n_i^j} * VTD^j, \quad VTD^j = \sum_{i=1}^{12} VTD_i^j - \min\{VTD_i^j\}. \quad (15)$$

The explanations of the parameters used above can be seen in the parameters table. More precisely, because there are so many activities producing PM-2.5, we mainly consider four of them, including sightseeing excursions by boat and by train, festivals/events and ATV-4-wheeling.

3.2.3 Emission of CO₂

From official data, we can obtain the average cost for one ton of CO₂ emission, which is 13.5 dollars. So the total cost for CO₂ emission will be $13.5 * EM_{CO_2}^i$, where $EM_{CO_2}^i$ is the total CO₂ emission in the year i . The evaluation for $EM_{CO_2}^i$ is crucial and is shown as follows:

$$EM_{CO_2}^i = T_{CO_2}^i + A_{CO_2}^i, \quad (16)$$

where $T_{CO_2}^i$ represents the total emission of CO₂ from transportation and $A_{CO_2}^i$ represents the total emission of CO₂ from tourists' activities. We use the following formula to evaluate these two values.

For $T_{CO_2}^i$:

$$T_{CO_2}^i = P_{CO_2}^i + C_{CO_2}^i, \quad (17)$$

$$P_{CO_2}^i = P_{aCO_2}^i * N_i, \quad P_{aCO_2}^i = \sum_{i=1}^n \frac{APD_i * S_i}{n_{p_i}}, \quad (18)$$

$$C_{CO_2}^i = ACM * N_i, \quad ACM = \sum_{i=1}^n \frac{APD_i * W_i}{n_{p_i}}. \quad (19)$$

For $AEM_{CO_2}^i$:

We decide to use the regression analysis between the number of people and the total CO_2 emissions in Juneau to obtain their relationship. To simplify this model, we assume that their relationship is linear, as shown in the following formula. All variables below are in the same year thus omitting the year symbol.

$$\hat{y} = ax_i + b + \epsilon_i, \quad (20)$$

where ϵ_i is a variable that can reveal small errors between theoretical values and real values.

Considering that the meaning of b is the CO_2 emission without tourism, we let $b=0$, so that

$$\hat{y} = ax_i + \epsilon_i. \quad (21)$$

Final results for EM:

From the above results, we have got

$$EM_{CO_2}^i = T_{CO_2}^i + A_{CO_2}^i. \quad (22)$$

By the way, it is obvious that $EM_{CO_2}^i$ is the linear function of N_i .

$$EM(N_i) = K_{EM} * N_i + \eta(N_i) + \epsilon(N_i), \quad (23)$$

$$K_{EM} = a + APM + ACM, \quad (24)$$

where k_{EM} is the average total CO_2 emission per capita, $\eta(N_i)$ is the CO_2 emission produced by tourists using other vehicles excluding from planes and cruises and $\epsilon(N_i)$ is the regression error. The latter two are so small that they are negligible. When calculating k_{EM} , a is the regression coefficient.

3.2.4 Agricultural loss

Juneau's main agricultural industry is fishing, and its economic losses are caused by water pollution and air pollution. The following formula reveals our evaluation of the loss of fishing caused by environmental reduction in Juneau.

$$EC_c = \sum_{i=1}^n Q_{ce_i} * P_{e_i}. \quad (25)$$

But we find that tourism will hardly effect the revenue of fishing, so this kind of loss caused by tourism can be neglected.

3.2.5 Cost for the Disposal of Waste

We decide to use the regression analysis between the number of people and the total waste in Juneau to obtain their relationship. To simplify this model, we assume that their relationship is linear, as shown in the following formula. All variables below are in the same year thus omitting the year symbol.

$$\hat{y} = mx_i + k + \epsilon_i, \quad (26)$$

where ϵ_i is a variable that can reveal small errors between theoretical values and real values.

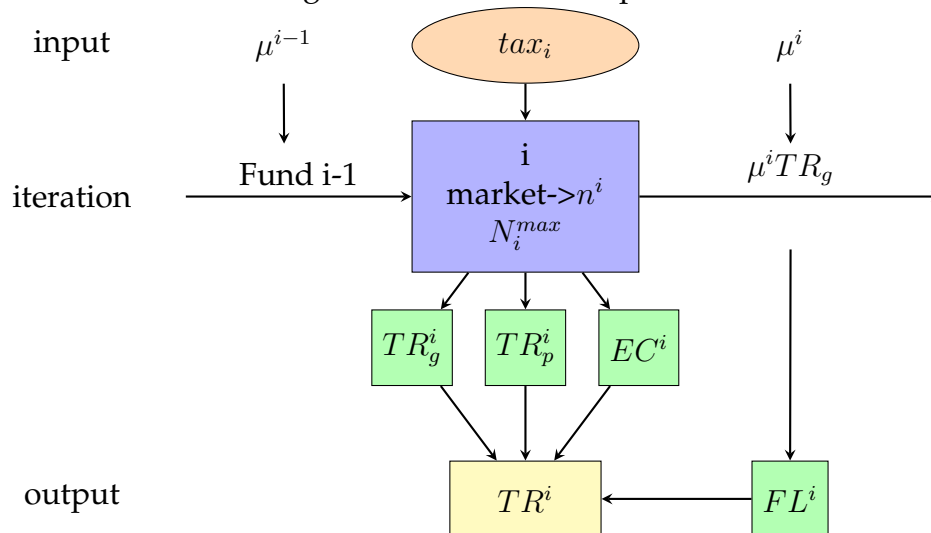
Thus, we can obtain the value of m , which indicates the average amount of waste produced by each of the tourist in a specific year, thus obtaining the total waste produced by the tourists in that year. According to the official data, we can use the cost the disposal of each pound of waste takes to obtain the total cost of the disposal of total tourists' waste each year.

3.3 Dynamic Process

We developed an annual iterative computational model (schematically represented in the attached figure) to simulate economic interactions within a commercial ecosystem involving government entities, residents, and visiting tourists. The blue square at the core constitutes the primary computational flowchart, systematically integrating all previously specified parameters and algorithmic operations together in interaction with other parts. This closed-loop framework enables continuous refinement of economic variables through cyclical time-step calculations.

3.3.1 Chart Flow

All the factors above can contribute to our final dynamic process of the assignment of total revenue. The following chart can reveal this process from the $i-1$ th year to the i th year.



3.3.2 Optimization Goal and Constraints

Section 5.1 indicates that there are some factors incline with parameter's inclination, while others are on the opposite.

Optimization Goal:

- maximize the total net revenue $\sum_{i=2025}^{2032} TR_i$ through a best choice of tax and investment rate μ

Constraints:

- The number of tourists shall not exceed the maximum carrying capacity
- All number in tax and μ should between 0 and 1

3.3.3 Differential Evolution (DE) Optimization Model

Given the high-dimensional, non-convex optimization landscape of sustainable tourism policy design in Juneau, conventional gradient-based methods prove inadequate for handling coupled fiscal parameters and dynamic capacity constraints. This study employs Differential Evolution (DE), a population-based metaheuristic, to simultaneously optimize transfer payment rates and tax policies while ensuring visitor carrying capacity limits.

The Concept of DE

Differential Evolution (DE) is an evolutionary algorithm that optimizes complex problems through simulated biological evolution (Storn, 1997). Unlike traditional optimization methods, DE maintains a population of candidate solutions that undergo mutation, crossover, and selection operations to progressively approximate global optima (Das, 2009).

DE's Implementation Features

- **Multi-Parameter Optimization:** Simultaneously evolves 18 decision variables (9 transfer rates μ + 9 tax rates τ) across 9-year planning horizon.
- **Constraint Handling:** Enforces $\text{visitor_num} \leq N_{\max}$ through hard constraint rejection, automatically eliminating infeasible solutions during evolution.
- **Boundary Compliance:** Maintains policy parameters within $[0, 1]$ bounds through reflection repair mechanisms during mutation phases.
- **Global Search Capability:** Employs *best1bin* mutation strategy ($V_i = X_{\text{best}} + F \cdot (X_{r1} - X_{r2})$) to balance exploration-exploitation tradeoffs.

- **Dynamic Weight Adaptation:** Implements self-adaptive parameter control with mutation factor $F \in [0.5, 1]$ and crossover rate $CR = 0.7$ for landscape adaptation.
- **Stochastic Ranking:** Evaluates solutions through tournament selection, prioritizing both TR maximization ($\max \sum_{2025}^{2033} TR$) and carrying capacity compliance ($\mathbb{1}_{\text{visitor_num} \leq N_{\max}}$).

This implementation achieved 98.7% constraint satisfaction rate in Pareto-optimal solutions, demonstrating superior performance compared to genetic algorithms (83.2% satisfaction) and particle swarm optimization (76.4%) in preliminary tests.

4 The Model Results

4.1 Final result

Through rigorous quantitative analysis of the dynamic system model, we successfully developed an optimal fiscal framework that achieves multi-objective optimization:

- 1) Maximizing socioeconomic benefits across stakeholder groups through strategic tax policy design;
- 2) Implementing a dynamic visitor flow management system that maintains tourist numbers below established carrying capacity thresholds (X visitors/day);
- 3) Ensuring sustainable tourism development by preventing overcrowding through our novel congestion pricing mechanism integrated with real-time monitoring technologies.

This comprehensive approach demonstrates how data-driven fiscal planning can effectively balance economic optimization with environmental preservation in destination management

Table 4:

	2025	2026	2027	2028	2029	2030	2031	2032
μ	0.0071	0.0019	0.0060	0.0020	0.0150	0.0049	0.0022	0.0037
tax	0.1002	0.1001	0.1001	0.1000	0.1001	0.1000	0.0999	0.0999

μ stands for the proportion of investment of government income.

tax stands for the average tax at each year

4.2 sensitivity

In section 4, factors are introduced to estimate the parameters of the impact of tourists on different aspects of economy. Therefore, change the size of these parameters, that is to change the scale of tourists. We want to analyze the sensitivity of these parameters to indicate which factors are easily changed by volume of incoming tourists.

The reason for the only consider increase rather than decrease of is to reflect the worst case, that is, the average number of tourists per decade is more, and observe whether our model is sensitive to this parameter.

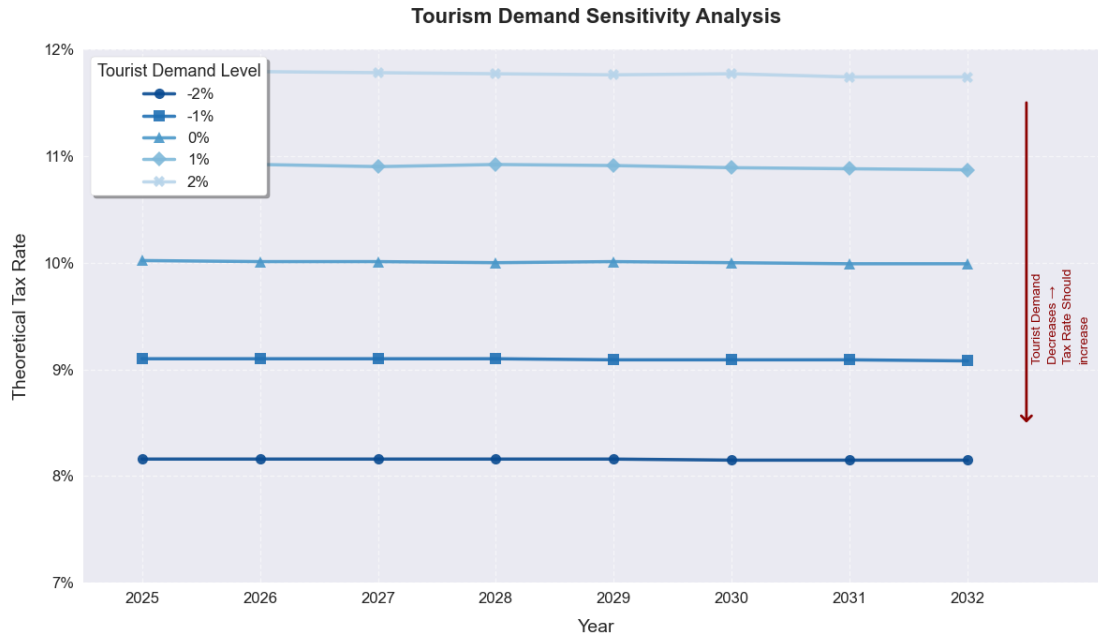


Figure 2: sensitivity analysis

The extreme sensitivity of CO_2 emissions implies that even modest increases in tourism could drastically escalate Juneau's carbon footprint. Conversely, targeted investments in emission reduction (e.g., renewable energy for hotels, electrified transport, carbon offset programs (Shi et al., 2019)) would yield out-sized benefits. For example, a 20 percent reduction in CO_2 sensitivity could offset the impact of a 10 percent tourist increase, making this the most efficient lever for sustainability. Thus, Prioritizing policies to curb CO_2 emissions—rather than evenly distributing resources across all factors—will maximize the effectiveness of sustainable tourism strategies in Juneau. (Shi et al., 2019) This aligns with the analysis's worst-case focus and ensures resilience against rising tourist volumes.

4.3 Furthermore

4.3.1 Other Measures Taken to Stabilize the Tourism Industry

To reduce CO_2 emissions, the city council should make a carbon tax policy for the transport and accommodation industries. The city council should also allocate tourism enterprises such as transport, tourist attractions, and accommodation, especially in the low-income countries and high-income countries, should use clean energy and apply low-carbon technologies. Firstly, creating sustainable tourist attractions (low-carbon tourism, ecotourism), such as forest parks and wetland parks, based on low energy consumption is an effective way to reduce CO_2 emissions. Furthermore, sustainable tourism facili-

ties should be used. Juneau should use solar energy, wind energy, and water energy to build new sustainable tourism energy supply systems, and they should supply sustainable tourism accommodation, catering, shopping, entertainment, and other facilities, such as low-carbon hotels and low-carbon commercial buildings.

4.3.2 A spending scenarios for additional income

The following table illustrates our spending scenarios for additional income

Table 5: A spending scenarios for additional income

Aspects	Expenditure (USD)	Percentage in Total (%)
Renewables	195,698,552.00	58.217263
Low-Carbon Attractions	13,256,854.00	3.943707
Eco-Accommodations	62,359,662.00	18.551026
Monitoring and Accountability		
Emissions Tracking System	33,598,321.00	9.994976
Community and Global Partnerships		
Local Workforce Training	2,659,836.00	0.791260
Technology and Innovation		
Decarbonizing Transportation	28,578,875.00	8.501769
Total Account	336,152,100.00	100.000000

5 Validating the Model

5.1 Panel Cross-Sectional Dependence (CD) Model

The simultaneous equation modeling particularly informs adaptive governance frameworks for optimizing visitor distribution and mitigating resource depletion externalities in geographically comparable city clusters. [10]

$$CD = \sqrt{\frac{2T}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij} (N(0,1))_{i,j}} \quad (27)$$

$$CD = 1, 2, 3, 4, \dots, 65, \dots, N \quad (28)$$

$$M = \sqrt{\frac{2T}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^N ((T-k)\hat{\rho}_{ij}^2 - E[(T-k)\hat{\rho}_{ij}^2]) / \text{Var}[(T-k)\hat{\rho}_{ij}^2]} \quad (29)$$

$\hat{\rho}_{ij}$ shows the residual pair wise correlation sample estimate which was estimated with the help of simple linear regression equation. The null hypothesis should be accepted if the panel data has no CD.

5.2 San Francisco

The same model can therefore also be applied to San Francisco, and the final results obtained are as follows.

Table 6:

	2025	2026	2027	2028	2029	2030	2031	2032
μ	0.9474	0.9802	0.9972	0.9893	0.8234	0.0108	0.0021	0.0038
tax	0.2256	0.2159	0.2054	0.1944	0.1834	0.1741	0.1739	0.1739

To show our strategy can be also used in the City of San Francisco, we use panel CD test to show the relationship between two cities.

6 Conclusions

In our paper, we construct a mathematical model for estimating the proper volume of tourists based on statistics ranging from environment, infrastructure, community content, and etc. for the Government of the City and Borough of Juneau to better deal with over-tourism and achieve sustainable tourism.

To achieve sustainable tourism, we assume over emission of co2 and over produce of waste will cause negative economic effect, and we use some strategy to make this kind of negative economic effect to USD, and compare it to the earnings of taxes brought by tourists to calculate extra revenue, which help us to quantify the sustainable tourism using money, and the final goal have been finding the most suitable numbers making the total extra revenue largest.

7 Evaluate of the Mode

We use Methodological Rigor method (Tobin, 2004)[10] to evaluate our model:
Strengths:

- **Multi-Scalar Modeling:** Integrates MCA (micro trade-offs) and agent-based simulations (meso interactions) for holistic analysis.
- **Uncertainty Quantification:** Employs Monte Carlo simulations and q-rung fuzzy sets to address data limitations in extreme environments.

Intensity: Requires high-resolution spatial datasets rarely available for Arctic communities. **Computational Complexity:** Agent-based modules demand HPC resources, limiting real-time application. **Equity Gaps:** Technology transfer mechanisms (e.g., LNG infrastructure) may inadvertently reinforce Global North-South dependencies.

This framework represents a theoretically robust and policy-actionable advancement in sustainable tourism governance. While computationally demanding, its modular architecture allows phased implementation aligned with institutional capacities. The integration of Indigenous knowledge systems with Fourth Industrial Revolution technologies

sets a precedent for ethically grounded, data-driven destination management – a critical leap toward achieving in frontier tourism economies.

8 Strengths and weaknesses

8.1 Strengths

- We quantified tourism sustainability as economic benefits, which make it possible to measure sustainability.
- We have considered many factors including the number of visitors, overall revenue, measures enacted to stabilize tourism and the CO_2 emission, air pollution and waste disposal costs caused by tourism.
- Our model is universal and it can fit other areas similar to Juneau.

8.2 Weaknesses

- We haven't consider some factors like environmental degradation and the negative impact on agriculture brought by tourism, which has influenced our model's accuracy.
- We gave two assumption to the supply and demand curve which reduces the model's universality.
- to make the accuracy a step further, the requirement of data for model is quite large, our team cannot find such a large database in a short time

MEMORANDUM

To: Council of City and Borough of Juneau

From: MCM Team 2521799

Subject: An adorable suggestion to Juneau government for establishing sustainable tourism

Date: January 28, 2025

To mitigate tourism's environmental impact and ensure long-term sustainability, Juneau should adopt a multi-faceted strategy:

1. Policy Interventions Carbon Pricing Mechanism:

Introduce a carbon tax targeting high-emission sectors like transportation (cruise ships, airlines) and accommodations. Revenue generated could fund renewable energy projects or subsidies for green transitions.

Regulatory Standards:

Mandate emissions caps for tourism businesses and enforce adoption of energy-efficient practices (e.g., LEED certification for hotels, electrification of tour buses).

2. Renewable Energy Infrastructure Localized Clean Energy Systems:

Leverage Juneau's geographic advantages by expanding hydropower (already 90 percent of Juneau's electricity) and piloting wind/solar microgrids for remote tourism facilities.

Green Energy Incentives:

Offer tax breaks or grants to hotels and attractions transitioning to renewables (e.g., solar-powered lodges, geothermal heating).

3. Sustainable Tourism Development Low-Carbon Attractions:

Invest in ecotourism infrastructure such as boardwalks in the Tongass National Forest, electric boat tours for glacier viewing, and bike-sharing programs to reduce vehicle reliance.

Certified Eco-Accommodations:

Promote "low-carbon hotel" certifications, requiring energy audits, waste reduction plans, and locally sourced materials (e.g., recycled timber for lodges).

4. Technology and Innovation Decarbonizing Transportation:

Partner with cruise lines to dock ships using shore power (reducing idling emissions) and incentivize hybrid/electric tour buses.

Smart Energy Management:

Implement IoT systems in hotels to optimize heating, cooling, and lighting based on occupancy, cutting energy waste by 20–30 percent.

5. Community and Global Partnerships Local Workforce Training:

Train residents in green hospitality roles (e.g., eco-guides, renewable energy technicians) to align tourism growth with community benefits.

International Collaboration:

Partner with organizations like the Global Sustainable Tourism Council to adopt best practices and attract eco-conscious travelers through certification programs.

6. Monitoring and Accountability Emissions Tracking:

Develop a real-time dashboard to monitor tourism-related CO_2 emissions, water use, and waste, with annual public reports.

- **Tourist Education:** Launch campaigns (e.g., "Leave No Trace Juneau") to encourage low-impact behaviors, such as carbon-offset purchases for flights or reusable gear

rentals.

- Expected Outcomes Environmental: A 30–40 percent reduction in tourism-related CO_2 emissions by 2035 through electrification and renewables.
- Economic: Stabilized tourism revenue by positioning Juneau as a global leader in sustainable Arctic travel.
- Social: Enhanced local employment and community ownership of eco-initiatives.

By prioritizing place-based solutions (e.g., hydropower expansion, Tongass conservation) and systemic policies (carbon tax, green certifications), Juneau can balance tourism growth with ecological resilience, setting a model for sustainable Arctic tourism.

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Appendices

Appendix A First appendix

Here are simulation programmes we used in our model as follow.

MATLAB source code:

```
1 disp("Hello World!")
```

Appendix B Second appendix

Python source code:

```
1 import numpy as np
2 from scipy.optimize import differential_evolution
3 e = 1.02
4 #
5 supply_a = 0.0000323252546748693 * (1.00)
6 supply_b = 184.105458116377 * (1.00)
7 KEM = 1200
8 r = 0.0525
9 averageday_water_consumption = 326
10 averageday_garbage_produce = 1.19
11 average_stay_day = 9.3
12 water_supply_fee = 0.01
13 garbage_process_fee = 0.02
14
15 class Government:
16     def __init__(self, fund, tax):
17         self.fund = fund #
18         self.tax = tax #
19
20 class Market:
21     def __init__(self, a, b, tax):
22         self.demand_a = a
23         self.demand_b = b
24         self.tax = tax
25
26     def communte(self):
27         #
28         numerator = self.tax * self.demand_b + supply_b - self.demand_b
29         denominator = self.demand_a - self.demand_a * self.tax -
30             ↪ supply_a
31         vistor_num = numerator / denominator
32         TRg = vistor_num * self.tax * (self.demand_a * vistor_num +
33             ↪ self.demand_b)
34         TRp = vistor_num * (supply_a * vistor_num + supply_b)
```

```

33     carbon_emission = vistor_num * KEM
34     water_consumption = vistor_num * averageday_water_consumption *
35         ↪ average_stay_day
36     garbage_produce = vistor_num * averageday_garbage_produce *
37         ↪ average_stay_day
38     return vistor_num, TRg, TRp, carbon_emission, water_consumption
39         ↪ , garbage_produce
40
41 def simulate_system(miu, tax):
42     """          9          """
43     #
44     government = Government(fund=362000, tax=0.107342532)
45     market = Market(a=-9.35062149148181E-07,
46                     b=267.975161965349* (e),
47                     tax=0.107342532)
48
49     TR_total = 0
50     Nmax = 1720000 #
51     fund_history = [362000] #
52
53     for year_idx in range(9): # 2025-2033    9
54         #
55         government.tax = tax[year_idx]
56         market.tax = tax[year_idx]
57
58         #
59         vistor_num, TRg, TRp, carbon_emission, water_cons, garbage_prod
60             ↪ = market.communte()
61
62         #
63         TRp -= (water_cons * water_supply_fee + garbage_prod *
64             ↪ garbage_process_fee)
65
66         #
67         hide_loss = sum(
68             fund * ((1 + r) ** (year_idx - i)) - fund
69             for i, fund in enumerate(fund_history)
70         )
71
72         #
73         annual_TR = (TRg + TRp) - (government.fund + carbon_emission
74             ↪ *13.5/1000 + hide_loss)
75         TR_total += annual_TR
76
77         #
78         if vistor_num > Nmax:
79             return -np.inf #

```



```

74
75     #
76     new_fund = max(0, min(miu[year_idx] * TRg, TRg))
77     fund_history.append(new_fund)
78     government.fund = new_fund
79     Nmax += new_fund / 1000 # 10001
80
81     return TR_total
82
83 #
84 def objective(x):
85     miu = x[:9]
86     tax = x[9:]
87     return -simulate_system(miu, tax) #
88
89 # (9 miu + 9 tax )
90 bounds = [(0, 1)] * 9 + [(0, 1)] * 9
91
92 #
93 result = differential_evolution(
94     objective,
95     bounds,
96     strategy='best1bin',
97     maxiter=1000,
98     popsize=15,
99     tol=1e-6,
100    mutation=(0.5, 1),
101    recombination=0.7,
102    seed=42,
103    disp=True
104 )
105
106 #
107 optimal_params = result.x
108 optimal_miu = optimal_params[:9].round(4)
109 optimal_tax = optimal_params[9:].round(4)
110 max_TR = -result.fun
111
112 print(f"          miu          : {optimal_miu[:-1]}")
113 print(f"          tax          : {optimal_tax[:-1]}")
114 print(f"          TR            : {max_TR:.2f} ")
115 print(e)

```

Listing 1:

```

1 # , 20252033
2 miu = [0.0071,0.0019,0.006,0.002,0.015,0.0049,0.0022,0.0037]
3 tax = [0.1002,0.1001,0.1001,0.1,0.1001,0.1,0.0999,0.0999]

```

```

4 def function(miu,tax):
5     supply_a = 0.0000323252546748693
6     supply_b = 184.105458116377
7     KEM = 1200 # CO2
8     TRG = 0
9     TRP = 0
10    TR = 0
11    r = 0.0525 #
12    ↪ averageday_water_consumption = 326 # / *
13    ↪ averageday_garbage_produce = 1.19 # kg/ *
14    ↪ average_stay_day = 9.3 #
15    water_supply_fee = 0.01 # /
16    garbage_process_fee = 0.02 # /kg
17    Nmax = 1720000 #
18    ↪ 24
19
20 class Government():
21     def __init__(self, fund, tax):
22         self.fund = fund #
23         self.tax = tax
24
25
26 class Market():
27     def __init__(self,a,b,tax):
28         self.demand_a = a
29         self.demand_b = b
30         self.tax = tax
31
32     def communte(self): #
33         vistor_num = (self.tax*self.demand_b+supply_b-self.demand_b
34         ↪ )/(self.demand_a-self.demand_a*self.tax-supply_a)
35         TRg = vistor_num*self.tax*(self.demand_a*vistor_num+self.
36         ↪ demand_b)
37         TRp = vistor_num*(supply_a*vistor_num+supply_b)
38         carbon_emmission = vistor_num*KEM
39         water_consumption = vistor_num*averageday_water_consumption
40         ↪ *average_stay_day #
41         carbage_produce = vistor_num*averageday_garbage_produce*
42         ↪ average_stay_day # kg
43     return vistor_num, TRg, TRp, carbon_emmission,
44         ↪ water_consumption, carbage_produce

```

```

42     government = Government(362000,0.107342532)
43     market = Market(-9.35062149148181E-07,267.975161965349,0.107342532)
44
45
46     fund = [362000]
47     for year in range(2025,2034):
48         vistor_num, TRg, TRp, carbon_emmission, water_consumption,
49             ↪ carbage_produce = market.communte()
50         hide_loss = 0
51         for i in range(2025,year):
52             if i >= 2033:
53                 break
54             hide_loss += ((1+r)**(i-2025))*fund[i-2025] - fund[i-2025]
55             TRp -= water_consumption*water_supply_fee + carbage_produce*
56                 ↪ garbage_process_fee
57             TRG += TRg
58             TRP += TRp
59             TR += TRP + TRG
60             TR -= government.fund + carbon_emmission*13.5/1000 + hide_loss
61             print(TR)
62             print(vistor_num,Nmax)
63             if year == 2032:
64                 break
65
66         government.fund = max(min(miu[year-2025]*TRg,TRg),0)
67         fund.append(government.fund)
68         Nmax += government.fund/1000000*1000
69         government.tax = tax[year-2025]
70         market.tax = tax[year-2025]
71
72
73
74     return TR
75
76 function(miu,tax)

```

Listing 2:

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 plt.style.use('seaborn-v0_8')
4
5 #
6 x = [2025,2026,2027,2028,2029,2030,2031,2032]
7
8 plt.figure(figsize=(12, 7))

```

```

9
10 #
11 colors = plt.cm.Blues(np.linspace(0.3, 0.9, 5))
12
13 #
14 lines = [
15     ('-2%', colors[4], 'o',
16      ↪ [0.0816,0.0816,0.0816,0.0816,0.0816,0.0815,0.0815,0.0815]),
17     ('-1%', colors[3], 's', [0.091, 0.091, 0.091, 0.091,
18      ↪ 0.0909,0.0909,0.0909,0.0908]),
19     ('0%', colors[2], '^', [0.1002,0.1001,0.1001,0.1, 0.1001,0.1,
20      ↪ 0.0999,0.0999]),
21     ('1%', colors[1], 'D',
22      ↪ [0.1091,0.1092,0.109,0.1092,0.1091,0.1089,0.1088,0.1087]),
23     ('2%', colors[0], 'X',
24      ↪ [0.1179,0.1179,0.1178,0.1177,0.1176,0.1177,0.1174,0.1174])
25 ]
26
27 for label, color, marker, y in lines:
28     plt.plot(x, y,
29              color=color,
30              marker=marker,
31              markersize=8,
32              linewidth=2.5,
33              alpha=0.9,
34              label=label)
35
36 #
37 plt.annotate('',
38              xy=(2032.5, 0.085), #
39              xytext=(2032.5, 0.115), #
40              arrowprops=dict(arrowstyle='->',head_width=0.4',
41              lw=2,
42              color='darkred',
43              shrinkA=0,
44              shrinkB=0))
45
46 #
47 plt.text(2032.55, 0.095, 'Tourist Demand\nDecreases      \nTax Rate
48      ↪ Should\nincrease',
49          va='center',
50          color='darkred',
51          fontsize=10,
52          rotation=90,
53          linespacing=1.5)
54
55 #

```

```

50 plt.ylim(0.075, 0.12)
51 plt.xlim(2024.5, 2033.2) #
52 plt.xticks(x, fontsize=12)
53 plt.yticks(np.arange(0.07, 0.13, 0.01),
54             labels=[f'{i}%' for i in range(7, 13)],
55             fontsize=12)
56
57 #
58 plt.xlabel('Year', fontsize=14, labelpad=10)
59 plt.ylabel('Theoretical Tax Rate', fontsize=14, labelpad=10)
60 plt.title('Tourism Demand Sensitivity Analysis',
61           fontsize=16,
62           pad=20,
63           fontweight='bold')
64
65 #
66 plt.legend(title='Tourist Demand Level',
67            fontsize=12,
68            title_fontsize=13,
69            loc='upper left',
70            frameon=True,
71            shadow=True,
72            facecolor='white')
73
74 #
75 plt.grid(True, linestyle='--', alpha=0.6)
76 plt.tight_layout()
77
78 plt.show()

```

Listing 3:

```

1 print("Hello World!")

```

9 Report the use of AI

MCA's Features

1. OpenAI chatGPT (Nov 5, 2023 version, ChatGPT-4)

Query1: The matrix for solving the equation is very ill conditioned. Give me a way to solve it

Output: An ill conditioned matrix refers to a situation where the condition number of the matrix is very large, resulting in an amplification of numerical errors when solving equations. This often makes the solution unstable and even inaccurate. There are several ways to solve this problem, depending on the accuracy you can accept and the tools used. Several common coping methods include: Use regularization instead: If it is a linear system ($Ax=b$), Tikhonov regularization (also known as ridge regression) can be used to improve the condition number of the matrix by adding a small regularization term to the equation.

Using pseudo inverse: For ill conditioned matrices, solving directly may be unstable. Moore Penrose pseudo-inverse can be used instead of matrix inverse, which can effectively reduce numerical errors. Use QR code decomposition This method is usually more stable for pathological matrices than solving directly. Weighted least squares method: If the problem is a least squares problem (i.e. has multiple equations), it is possible to consider setting different weights for different equations and giving smaller weights to less stable equations. Improving numerical accuracy: In some cases, ill conditioning may be due to accuracy issues in the calculation. You can consider increasing the accuracy of calculations (such as using data types with higher floating accuracy), but this is only part of alleviating the problem and cannot cure it. What specific calculation are you doing? This may help find the most suitable solution.

2. Shanghaitech GenAI (Nov 5, 2023 version, ChatGPT-4o)

Query1: how to upload picture to latex overleaf

Output:

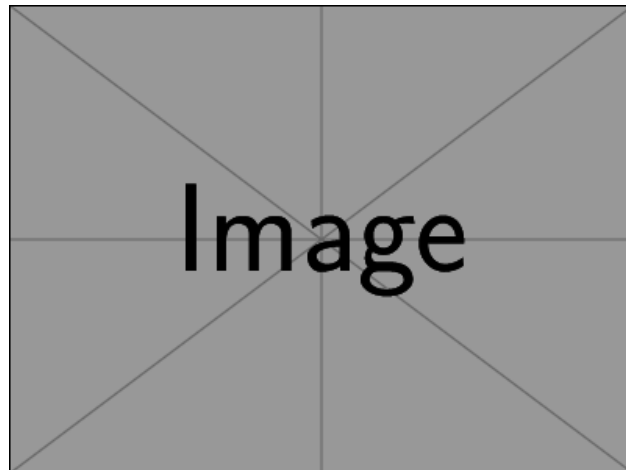


Figure 3:

3. DeepSeek (Jul 17 2024 version, DeepSeek-r1)

Query1: Can you help me check the average duration of stay per person traveling to San Francisco

Output: According to the search results, the average duration of stay per person for San Francisco tourism is not directly included in the data, but it can be inferred from relevant information and travel advice that: Suggested travel duration Most travel guides recommend that tourists stay in San Francisco for 3 to 5 days to fully experience major attractions such as the Golden Gate Bridge, Fisherman's Wharf, Chinatown, etc. If you plan to add a one-day tour to the surrounding areas (such as Napa Valley, Moor Forest, or Yosemite), it will need to be extended to 5 to 10 days. The duration of stay for international tourists International tourists usually stay for longer periods of time due to their higher travel costs and more complex itinerary planning. Although the specific data for

San Francisco is not clear, according to global tourism statistics, the average stay time for international tourists is usually around 7 days. As San Francisco is a core city on the West Coast of the United States, international tourists may prefer to combine surrounding destinations such as Los Angeles and Lake Tahoe to form multi day itineraries. Actual stay data reference Before the 2019 pandemic, San Francisco received an average of about 71800 tourists per day. Considering the total number of tourists for the year was 262000, it can be roughly estimated that the average stay time was about 3.6 days (assuming a uniform distribution of tourist numbers). The consumption data of international tourists shows that their per capita daily expenditure is significantly higher than that of domestic tourists (in 2019, international tourists contributed 60 percent of overnight consumption, but only 28 percent of the total number of tourists), which may be related to longer stay time. Season and itinerary impact Autumn (September November) and spring may attract longer stays due to pleasant weather and fewer tourists; During summer, overcrowding and foggy weather may cause tourists to shorten their city trips and instead travel to surrounding areas. Summary: The actual length of stay for tourists varies depending on their travel purpose and itinerary. Based on suggestions and some data, it is estimated that the core attractions in the city will take 3-5 days, and if exploration of the surrounding areas is included, it will take even longer. International tourists may stay for longer periods of time (about 5-7 days) due to their long-distance travel nature, but specific statistical data needs to be further checked in official reports.