
Make Tourism Sustainable Again: Take Juneau as an Example

Summary

With a growing influx of tourists, Juneau, Alaska finds itself at a crossroads, grappling with environmental challenges like accelerated glacier melt and increasing societal pressures, all while reaping substantial economic rewards. Consequently, the government is urgently seeking a sustainable tourism blueprint that can foster tourism growth, and effectively combat environmental challenges. This paper introduces a comprehensive revenue model to evaluate sustainable tourism strategies within the present urban fabric. Furthermore, it proposes a policy game model rooted in this framework to intricately map out policy interconnections and offer optimal implementation strategies.

For Task 1, we first developed a **revenue maximization model (RMM)** based on the relation between raw tourism revenue, environmental constraint and social welfare to evaluate the **comprehensive revenue** with no policy involved. Our optimization findings obtained by the **simulated annealing algorithm** suggest that maximizing peak-season tourism revenue necessitates limiting glacier area visitors to approximately 35-55% of total tourists, while also maintaining accommodation distribution in the main city within the range of 20-40% of total visitors.

For the remaining questions in Task 1, we developed a **evolutionary revenue maximization model** based on the **evolutionary game theory**. By introducing three stakeholders of the game, we constructed and solved the **replicator dynamics equations**, successfully obtained the one-and-only **non-trivial equilibrium solution** in its analytical form. The strategy of policies can be explicitly demonstrated by the form derived from the model.

For Task 2, we transplanted the RMM model to Venice, Italy, adapting the environmental constraint function accordingly. The simulation outcomes indicate a comparable accommodation strategy to that of Juneau, Alaska, yet reveal contrasting environmental strategies. This outcome implies that tourist cities with varying **congestion levels** should tailor their focus on environmental and infrastructure allocation strategies accordingly.

Finally we conducted a sensitivity analysis on the revenue maximization model(RMM) and the **environmental constraint model** encompassed by the RMM. With the parameter space varying between [80%, 120%], both the comprehensive revenue and the vast majority of parameters remains stable. The model also highlights five key parameters that significantly impact comprehensive revenue, including carbon emissions per capita, individual consumption levels, and environmental constraint parameters. These factors offer valuable insights for guiding policy development in the desired direction.

Keywords: revenue maximization model; evolutionary game theory; replicator dynamics equation; simulated annealing algorithm; comprehensive revenue

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1 Introduction

1.1 Background

The city of Juneau, Alaska, USA, with a population of around 30,000 residents, welcomed over 1.6 million cruise visitors in total in 2023.[1] The region's stunning natural landscape, including its glaciers and national parks, has been a key driver of tourism, significantly contributing to the city's revenue in recent years. However, this influx of tourists has also brought about many challenges. The impact of tourists on glaciers has accelerated their melting[2], while the strain of over-tourism has placed significant pressure on the city's infrastructure, emphasizing the urgent need for sustainable tourism policies.[3, 4]



Figure 1: Landscape of Juneau, Alaska

To promote the sustainable growth of the tourism sector in Juneau, the city government is now exploring the invisible burden associated with tourism infrastructure development, as well as quantifiable environmental metrics such as carbon emissions footprint. By establishing a comprehensive sustainable tourism model grounded in these factors, Juneau can not only enhance its tourism industry but also serve as a valuable reference point for other tourist-heavy cities globally.

1.2 Restatement

For the requirements and tasks given, we restate them to help better position the focus of our work.

- **Task 1:** Develop a multivariate sustainable tourism model to quantify the interplay among tourism revenues, visitor footfall, demographic dispersion, urban infrastructure, and latent

costs within Juneau City's tourism sector, with the overarching goal of pinpointing the optimal solution.

- **Task 2:** Conduct an in-depth analysis of the impact of tourism revenues on urban infrastructure and the tourism system in Juneau City. Explore the complexities of optimizing tourism benefits under these conditions, examining the influence of policies on this optimization process and identifying key factors that significantly affect the outcomes.
- **Task 3:** Transfer the model to other tourist-saturated destinations for validation and conduct targeted analyses on the selected cities. Then offer strategic policy recommendations to enhance the sustainable development of local tourism.
- **Task 4:** Write a memo summarizing the results and giving targeted advice to Juneau government.

1.3 Our Work

To address the mentioned issues, our work can be illustrated with the following flowchart:

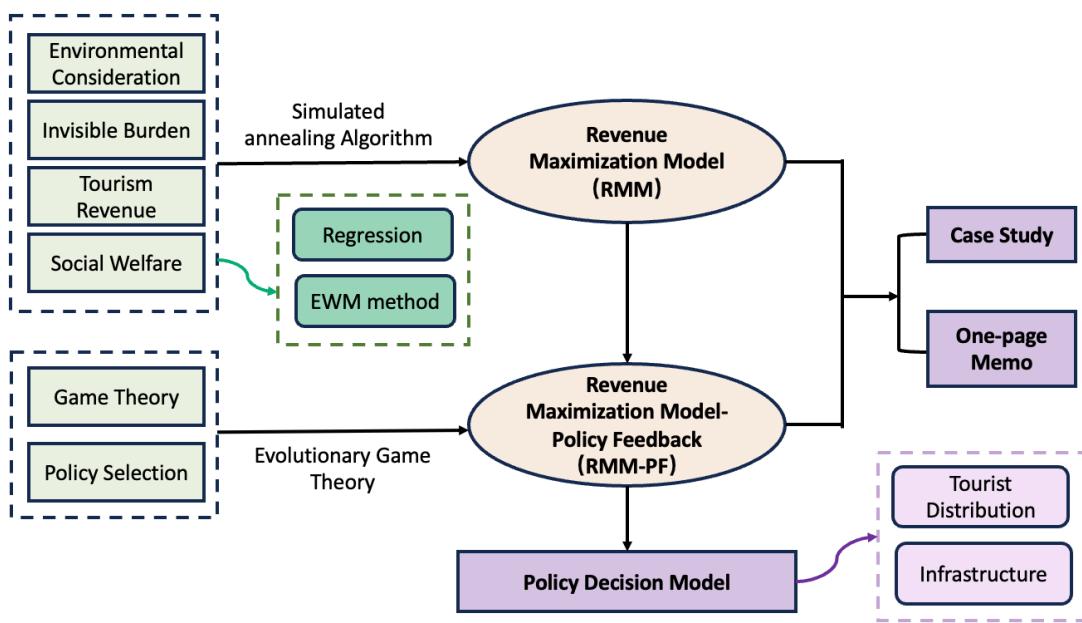


Figure 2: Flow chart for our work

2 Assumptions and Justifications

To simplify the problem and make it convenient for us to simulate real-life conditions, we make the following basic assumptions, each of which is properly justified.

- **Assumption 1:** Assume that sustainable tourism in Juneau is defined as an approach that aims to balance economic benefits with environmental protection and urban living standards.

Justification 1: The burgeoning tourist numbers offer Juneau a substantial revenue stream, yet they also pose challenges to the local natural environment, infrastructure, and urban residents' quality of life. Consequently, cultivating a robust and sustainable tourism industry mandates a delicate balancing act among these crucial facets.

- **Assumption 2:** Assume that in popular tourist attractions such as glacier visits and whale-watching excursions, visitor satisfaction is expected to exceed that derived from lesser-known or niche destinations.

Justification 2: The development and commercialization of popular attractions often outshine those of less frequented sites. In Juneau, the city's prominent natural wonders, coupled with a diverse range of travel experiences, are poised to offer visitors enhanced satisfaction, amplified by compelling promotional strategies.

- **Assumption 3:** Assume that the number of people in Juneau during the day and night is the same.

Justification 3: According to the 2023 Alaska VISITOR PROFILE REPORT, the average length of stay is around 8.3 days.[5] Over this relatively long period of time, it can be assumed that visitors also stay in the primary destination of the City of Juneau for a relatively long point in time, creating a relatively steady volume of visitors, i.e., the number of nighttime visitors is equal to that of daytime visitors.



Figure 3: Data from Alaska visitor profile

3 Notations

In the following table we list some of the symbols and definitions we use.

Symbols	Definition
$\vec{x} = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]$	Tourist distribution vector
$x_0 = \sum_{i=1}^4 x_i = \sum_{j=5}^7 x_j$	Total number of tourists
x_1	Number of tourists in the urban area
x_2	Number of tourists in the glacier scenic area
x_3	Number of tourists in scenic spots other than the glacier
x_4	Number of tourists in less hyped areas
x_5	Number of tourists staying in the main urban area (with a significant impact on local residents)
x_6	Number of tourists staying in the suburbs (with a smaller impact on local residents)
x_7	Number of tourists staying in tourist areas (with no impact on local residents)
R	Total tourism revenue
G	The glacier recession index
C	The carbon footprint index
E	Environmental constraint factor
Q	The invisible burden
N	Comprehensive revenue of sustainable tourism
W	Social welfare
F	Residential infrastructure holdings

4 Revenue Maximization Model without Policy Feedback

To compute the comprehensive revenue N in the tourism industry, the result should encompass the original income, the invisible burden associated with tourism expenditures, and the constraints imposed by potential environmental degradation. The calculation of N involves considering the tourist distribution vector as an independent variable, where the total number of tourists and their specific distribution in the scenic areas directly determine the magnitudes of the aforementioned aspects. Invisible burden, considered as expenditures, require subtraction from the original income. Additionally, the environmental constraints act as a scalar factor that impacts both the original income and the invisible burden, forming the mathematical expression for the comprehensive revenue N .

$$N = E \times [R - Q(F, W)] \quad (1)$$

4.1 Environmental Constraint Assessment

Empirically, the environmental factor should predominantly reflect the most significant among various environmental effects. Hence, we can specify its form as $E(\max(G, C))$, whereby both G and C are normalized to discern which effect holds greater significance. In accordance with the demands of sustainable tourism, when the impacts of G and C tend towards unity, thus approaching the environmental protection threshold, the influence of the environmental factor on comprehensive revenue should markedly intensify. This condition can be mathematically formulated as follows:

$$E(\max(G, C)) \quad s.t. \quad E(t) = \begin{cases} \text{descend rapidly when approaching 1,} & t < 1 \\ 0, & t \geq 1 \end{cases} \quad (2)$$

Taking into account the continuity of the objective function N, we construct a continuous and differentiable environmental factor function. This function is designed to exhibit **exponential decay** as it approaches unity, while remaining steady (i.e., at zero) at other times.

$$E(t) = \begin{cases} e^{-\frac{a}{1-t}}, & t < 1 \\ 0, & t \geq 1 \end{cases} \quad (3)$$

The shape of $E(t)$ is exhibited in the figure below:

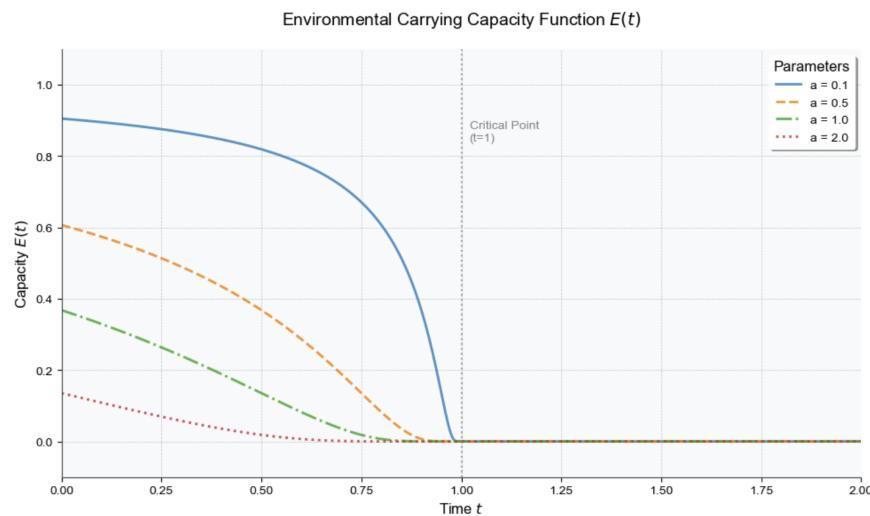


Figure 4: E-t relation with varied parameter a

4.1.1 Glacier recession model

To normalize the glacier melt index G effectively, the raw glacier melt area data should be divided by the permissible melting limit G_{max} , ensuring that G falls within the range of 0 to 1, that is $G = G_{raw}/G_{max}$.

4.1.2 Carbon footprint assessment

The carbon emissions in the tourism industry stem from various sources, including transportation, accommodation, and dining .etc. Each tourist visiting Juneau contributes to the city's carbon footprint during their sightseeing experience.

According to the research on the Carbon footprint of tourism in Barcelona[6], over 95% of the carbon emissions from tourism are linked to the transportation used for arrivals and departures. Hence, the carbon emissions attributable to cruises and air travel can be indicative of the overall carbon impact brought by tourists, suggesting a primarily linear relationship when averaged. Consequently, the relationship between carbon footprint and tourist numbers can be characterized using a linear model, denoted as $C = x_0 \times C_{per_tourist}$. Similar to the glacier recession index G, the carbon footprint index also requires normalization, satisfying $C = C_{raw}/C_{max}$. The estimation process and methods for the carbon footprint is demonstrated in the diagram below:

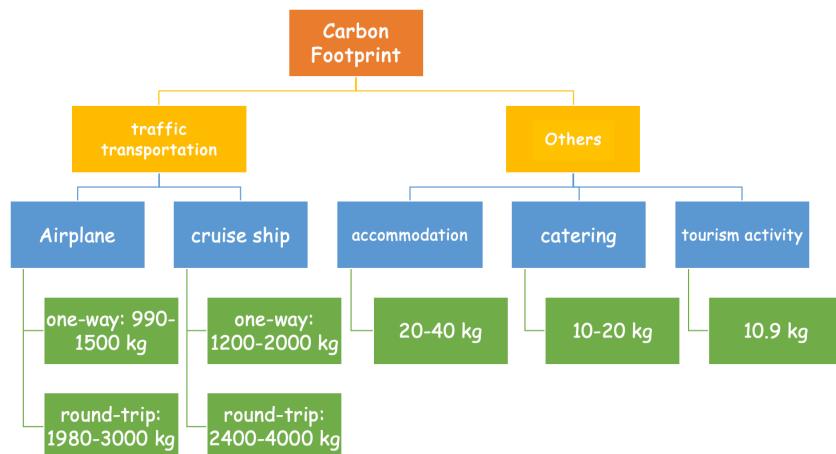


Figure 5: Comprehensive analysis of carbon footprint generated in the whole process of tourism in Juneau

In this assessment, drawing from the carbon emission methodologies of the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA)[7], the carbon output per traveler hovers around 0.33 to 0.5 kilograms of CO₂ per kilometer for a standard 3000-kilometer voyage (predominantly U.S.-based tourists). Meanwhile, for a typical 1000-kilometer journey, each passenger's carbon emission ranges from 1.2 to 2 kilograms of CO₂ per kilometer.

The final calculation approximates that the cumulative carbon footprint per visitor arriving in Juneau (inclusive of round-trip commutes) falls within the bracket of 2010.9 to 3070.9 kilograms of CO₂ (for air travel) or 2430.9 to 4060.9 kilograms of CO₂ (if traversing by cruise).

4.2 Hidden Burden Assessment

In the process of promoting ecotourism, the concept of hidden costs is frequently discussed. In Wood's report[8], hidden costs are defined as "the undisclosed expenses related to maintaining local

infrastructure and safeguarding ecological and social-cultural systems for tourists and residents.” In this model, we constructed a binary modeling of hidden costs. From the above definition, it is evident that hidden costs are intertwined with the infrastructure requirements and the interactions between tourists and residents. Therefore, we abstract the interactions between tourists and residents as a multidimensional composition of social welfare. This abstraction, coupled with an index-form infrastructure condition, is therefore utilized to gauge the hidden cost component within the comprehensive benefits of sustainable tourism.

The equation for $Q(F, W)$ is listed below:

$$Q = W \times \left[1 + e^{\left(\frac{F(x_0)}{D} \right)^b} \right] \quad b \sim 5 \quad (4)$$

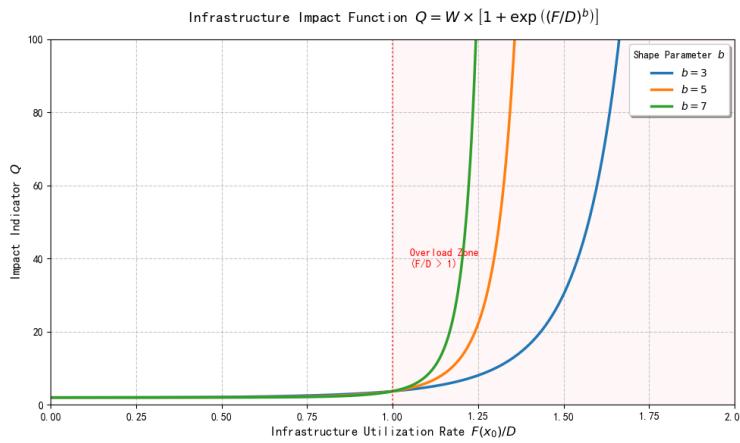


Figure 6: Curve of the Q function

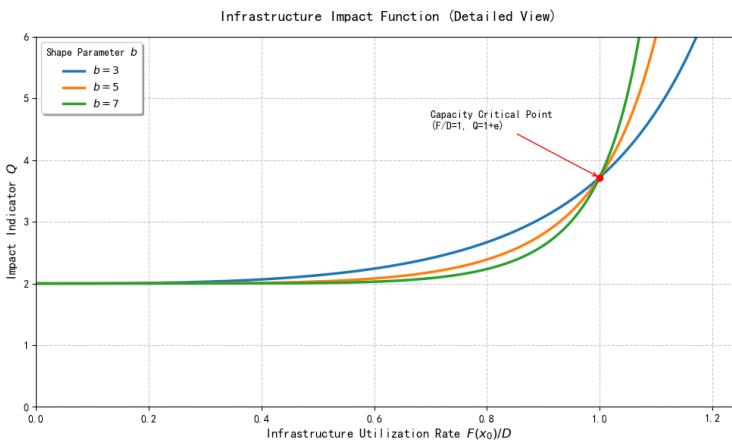


Figure 7: Curve of the Q function (detailed view)

From the figure above, the impact of invisible burden increases with a growing rate of infrastructure utilization. However, the impact is in general small, which is in accordance with the reality that the invisible burden won't shift in a short period of time.

4.2.1 Social welfare model

In most cases, "social welfare" is perceived as an abstract portrayal of the overall well-being of all party in society. In our model, the concept of social welfare is extended to substantial dimensions, aiming to signify the economic costs associated with the collective decline in well-being across all societal factions. The social welfare function $W(w_1, w_2, w_3, w_4)$ can then be constructed as a linear combination of four parameters, denoted as resident burden(w_1), residential infrastructure occupancy rate(w_2), resident satisfaction(w_3), and tourist satisfaction(w_4), correspondingly.

$$W(w_1, w_2, w_3, w_4) = \alpha_1 w_1 + \alpha_2 w_2 + \alpha_3 w_3 + \alpha_4 w_4 \quad (5)$$

The definition and calculation methodology of all parameters is demonstrated in the graph presented below:

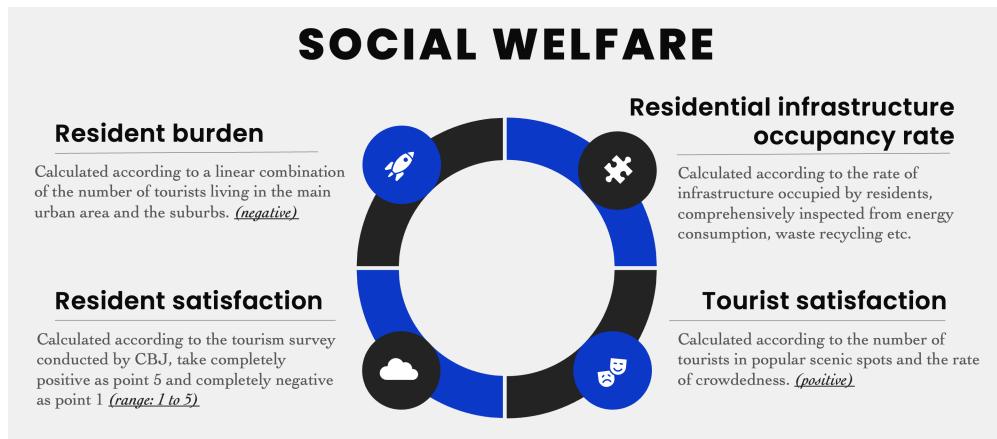


Figure 8: Components of the social welfare model

Since the definition of social welfare is indeed abstract, the model has to follow a branch of procedures to project this abstract index to the substantial dimension. The procedures are listed in the flow chart below.

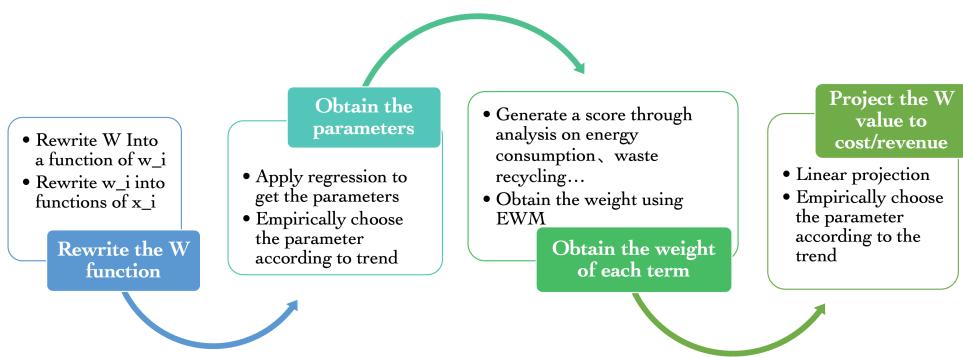


Figure 9: Procedures of calculating the social welfare function

To effectively calculate the value of $W(w_1, w_2, w_3, w_4)$, the social welfare model requires specific functional forms for the parameters respectively, which are selected **empirically or through regression** on the original data. The results and parameter explanation are listed below.

$$w_1 = \frac{(-c_1x_5 - c_2x_6)}{X} \quad (6)$$

$$w_2 = -4\left(\frac{2F}{D} - 1\right)^2 + 5 \quad (7)$$

$$w_3 = kx_0 + b \quad (8)$$

$$w_4 = 3 + c_3 \left(1 - \frac{x_2 + x_3}{y_2 + y_3}\right) + c_4 \left(1 - \frac{x_4}{y_4}\right) \quad (9)$$

Symbols	Definition
X	Normalization parameter
D	Infrastructure cap
y_2	Maximum number of tourists in the glacier area
y_3	Maximum number of tourists in other hiped area
y_4	Maximum number of tourists in other area
c_1	Residential burden parameter
c_2	Residential burden parameter

Parameter c_1 and c_2 is calculated by the formula:

$$\begin{cases} c_1 = \left(\frac{\text{Juneau average housing price in the main urban area}}{\text{Juneau average disposable income}} / \frac{\text{American capital average housing price}}{\text{American capital average disposable income}} - 1 \right) \\ \quad \times \text{Juneau average housing price in the main urban area} \times \text{property tax rate} \\ c_2 = \left(\frac{\text{Juneau average housing price in the secondary urban area}}{\text{Juneau average disposable income}} / \frac{\text{American capital average housing price}}{\text{American capital average disposable income}} - 1 \right) \\ \quad \times \text{Juneau average housing price in the secondary urban area} \times \text{property tax rate} \end{cases}$$

To measure the relative importance between the indices, the **entropy-weighed method** can be employed. We first perform normalization operations on the data, where row vector elements are objects and column vector elements are indicators.

$$\begin{cases} x'_{ij} = \frac{X_{ij} - \min(X_{1j}, X_{2j}, \dots, X_{nj})}{\max(X_{1j}, X_{2j}, \dots, X_{nj}) - \min(X_{1j}, X_{2j}, \dots, X_{nj})} \\ x'_{ij} = \frac{\max(X_{1j}, X_{2j}, \dots, X_{nj}) - X_{ij}}{\max(X_{1j}, X_{2j}, \dots, X_{nj}) - \min(X_{1j}, X_{2j}, \dots, X_{nj})} \end{cases} \quad (10)$$

Assuming that there are n objects to be evaluated and m indicators, the weight of the i th object under the j th indicator can be expressed in the following form:

$$y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^m x'_{ij}} (i = 1, 2, \dots, n; j = 1, 2, \dots, m) \quad (11)$$

Then the information entropy is given by:

$$e_j = -\frac{1}{lnm} \sum_{i=1}^m y_{ij} \ln y_{ij} \quad (12)$$

The weight of each index is given by:

$$w_j = \frac{1 - e_j}{m - \sum_{j=1}^m e_j} \quad (13)$$

The results are $w_1 = 0.4684$, $w_2 = 0.2939$, $w_3 = 0.1511$, $w_4 = 0.0866$ respectively.[AI: 1]

4.3 Model Results

From the analysis above, it can be concluded that the optimization objective function as well as the constraints of the model need to adhere to the mathematical structure shown below:

Objective function:

$$N = E \times [R - Q(F, W)] \quad (14)$$

Constraints with their detailed mathematical expression discussed in previous sections:

$$E(t) \in (0, 1) \quad (15)$$

$$Q = -W \times \left[1 + e^{\left(\frac{F(x_0)}{D} \right)^b} \right] \quad b \sim 5 \quad (16)$$

$$W(w_1, w_2, w_3, w_4) > V = W_{min} \quad (17)$$

After applying the **simulated annealing algorithm** for optimizing the objective function N, the maximum gains of N are observed to be [694470.03, 1453392.93, 1639947.79, 1907770.20] dollars at x_0 values of **5000, 10000, 15000, and 20000** respectively. Upon examination of the heat map, it becomes evident that these peak gains consistently occur at low main city lodging rates and a reduced proportion of glacier tourists. The general trend depicted by the contours appears linear; however, there are nuanced non-linear influences at play. For instance, around 15000 tourists, the presence of glaciers in high-yield zones and the quantity of lodging in the main city exhibit nearly equivalent impacts on the gain. In the contrast, as the tourist count surpasses 20000, the number of glaciers in high-yield areas significantly outweighs the importance of main city lodging in determining gains.

This outcome harmonizes with the reality where the main urban area experiences heightened residential infrastructure occupancy. As tourist saturation transpires in the main urban locale, revenue outcomes predominantly pivot on the environmental ramifications stemming from glacier numbers. It can also be obtained from the simulation results that when the tourist number is 15000 and 20000 respectively, the proportion of visitor traveling to the glacier will be limited. When the comprehensive revenue reaches the maximum value, the corresponding ratio takes values of 0.56 and 0.39 respectively.

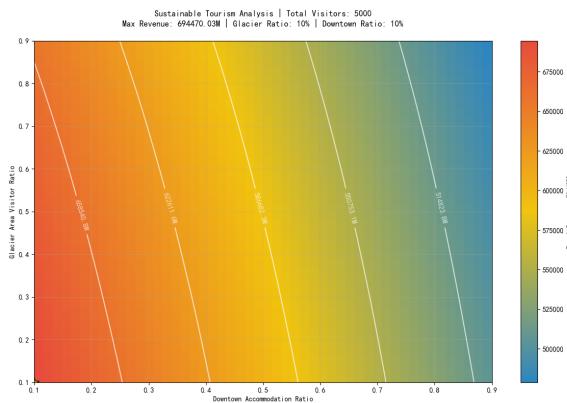


Figure 10: Tourist number = 5000

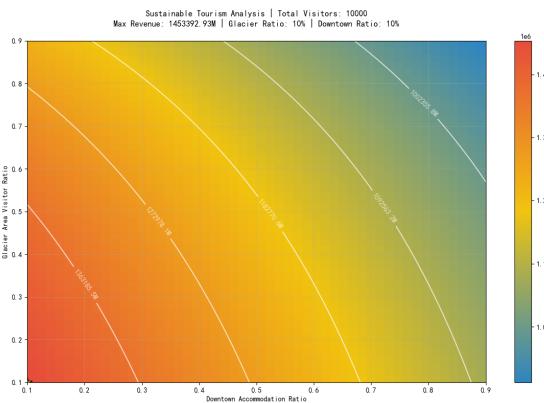


Figure 11: Tourist number = 10000

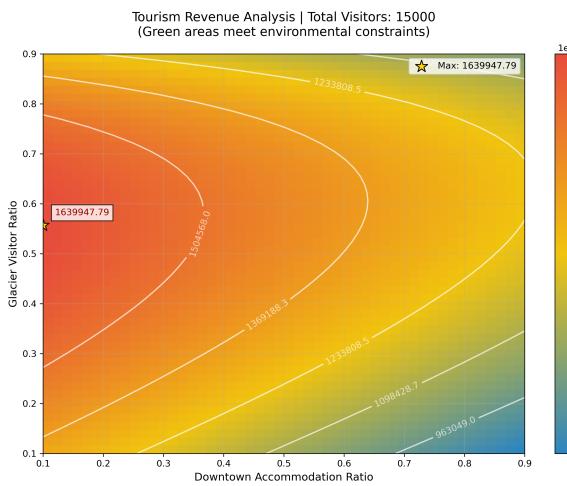


Figure 12: Tourist number = 15000

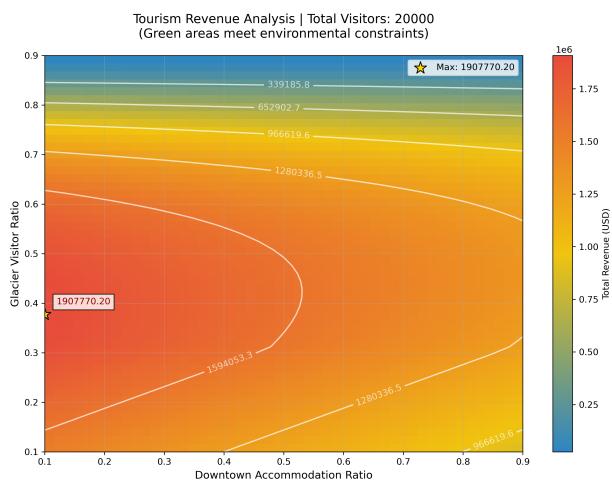


Figure 13: Tourist number = 20000

5 Evolutionary Game Theory Model with Policy Feedback

Evolutionary game theory is a framework that combines the theoretical analysis of game theory with the dynamics of evolutionary processes. It originates from the theory of evolution in biology and is used to address complex game structures that deviate from the "perfectly rational individual" assumption. One of the most classic and pioneering concepts in this field is the "evolutionarily stable strategy" (ESS) proposed by Maynard Smith and Price in 1973. [possible citation]

Since the 1990s, a growing number of game theory experts, as well as social scientists have incorporated biological evolutionary game theory(BEGT) into the study of social issues. This approach has been particularly useful for explaining the evolution of social institutions, the formation of social habits, and the establishment of social norms. Over time, it has provided a new perspective within game theory.

Evolutionary game theory reexamines the concept of game equilibrium from an evolutionary standpoint, relaxing the assumption of perfect rationality and offering a novel method to perform **Nash equilibrium** and **equilibrium selection**.

Here, we introduce an evolutionary game model with policy feedback(RMM-PF), using the **replicator dynamics method** to identify a **non-trivial evolutionarily stable strategy**. This approach is used to plan for expenditures from any additional revenue and to demonstrate how these expenditures feed back into the model to promote sustainable tourism as a whole.

5.1 Assumptions of the game model

5.1.1 Policy

For expenditures from any additional revenue, we summarize three policies exerting great influence on sustainable tourism. Each policy feeds back into our model with its complementary effects.

Policy I multi-dimensional limitation to the number of visitors

Policy II multi-faceted improvements to infrastructure

Policy III multi-level balancing community development

Policy I will limit the daily upper bound for tourist arrivals (x_0 in our model) and guide them to visit more sustainable attractions, and thus improving the distribution of tourists (\vec{x} in our model). Take C_a as the cost of feedback to the comprehensive revenue of sustainable tourism (N in our model).

Policy II will gradually improve the state of infrastructure development by upgrading and renovating outdated infrastructure and by reasonably planning new projects. This will alleviate the pressure of urban traffic, overcrowdedness and so on. It will also increase the infrastructure capacity limit (D in our model), thereby raising the residential infrastructure occupancy rate (w_2 in our model), and will ultimately enhance social welfare. Take C_b as the cost of feedback into N .

Policy III will balance community development, enhance community values, and increase social capital as well, thereby alleviating residents' burdens (w_1 in our model) and gradually improving residents' satisfaction (w_3 in our model). Ultimately it will enhance social well-being. Take C_c as the cost of feedback into N .

To make a decision to implement the policy combination, we firstly consider the expenditures constraint. With summing the additional revenue to C_{tot} , there must be a constraint constituted by the abstract cost of the policies above.

$$XC_a + YC_b + ZC_c = C_{\text{tot}} \quad (18)$$

The parameters X, Y, Z can be simultaneously understood as de-abstractions of part of construction of the game model (x, y, z) as described in Table 1.

5.1.2 Parameters

Based on the outlined policies, three distinct stakeholders can be identified within the policy framework: local governments, the tourism bureau, and residents (namely, local inhabitants). It is plausible to consider these stakeholders as integral components of a system responsible for determining the policy amalgamation in the evolutionary game model.

- **Restriction(R):** Due to the expenditure constraint discussed above, when applying two policies simultaneously, there will be mutual restriction to corresponding stakeholders described as R .
- **Benefits(B):** Consider the influence of policy to the stakeholders. It cannot be ignored that the implementation of any policy inherently provides corresponding benefits to the stakeholders, described as B .
- **Residential Damage(D_b and D_c):** Given the stability of local governments, the impact of Policy I on the government itself can be ignored. Subsequently, the damage caused to the tourism bureau by not improving infrastructure and the damage caused to residents by unbalanced development can be denoted as D_b and D_c , respectively.
- **Affect(A_b and A_c):** Consider apparent impact of tourism bureau and residents on the local government. Therefore, the support to improve infrastructure is set to A_b while that to balance community development is set A_c .
- **Tourism Damage(P_a and Q_a):** When there is no limitation on the number of visitors, the overcrowded tourists and the distribution of tourists that do not support sustainable tourism will intuitively cause corresponding damage to both the tourism bureau and the residents. The damage caused by unrestricted tourists to the tourism bureau can be quantified as P_a , and that caused by unrestricted tourists to the residents as Q_a .

Some detailed interactions should be encompassed into the payoff matrix as well. When both infrastructure improvement and the community development balance are achieved, the two policies will mutually promote each other, resulting in payoffs for the tourism bureau and local residents that can be abstracted as roughly similar described as T . At the same time, in the case of a balanced community development, residents will naturally have a higher demand for infrastructure quality. If infrastructure is not updated at this time, the local government will impose corresponding penalties on the tourism bureau, quantified as L .

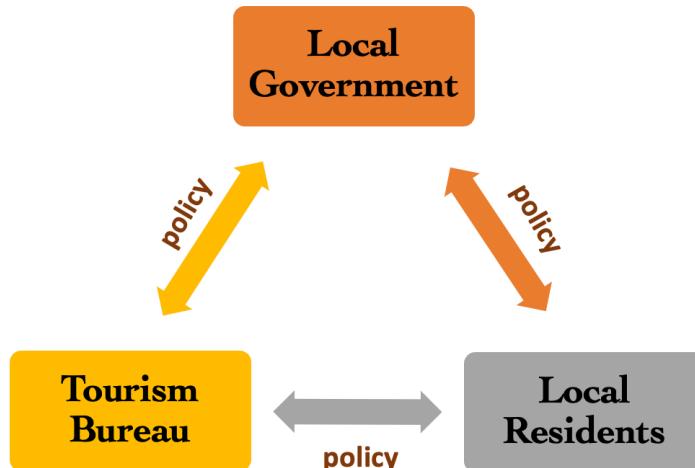


Figure 14: Procedures of calculating the social welfare function

Table 1: Symbol and Parameter Description

Parameter	Meaning
$R_{xy} \approx R_{yx}$	Correlation coefficient between the costs of implementing Policy I and Policy II payments
$R_{yz} \approx R_{zy}$	Correlation coefficient between the costs of implementing Policy II and Policy III payments
$R_{zx} \approx R_{xz}$	Correlation coefficient between the costs of implementing Policy III and Policy I payments
B_a	Benefit of Policy I for the local government itself
B_b	Benefit of Policy II for the tourism bureau itself
B_c	Benefit of Policy III for the residents itself
D_b	Damage caused to the tourism bureau by not improving infrastructure
D_c	Damage caused to residents by unbalanced development
A_b	Support to the government in improving infrastructure
A_c	Support to the government in balancing community development
P_a	Damage caused by unrestricted tourists to the tourism bureau
Q_a	Damage caused by unrestricted tourists to the residents
T	Mutually promotion with Policy II and Policy III
L	Penalties imposed by local governments on tourism bureaus when the community is already experiencing balanced development, and infrastructure has not been improved
x	Probability of limiting the number of visitors
y	Probability of improving infrastructure
z	Probability of balancing community development

5.2 Model framework

Based on the model hypotheses, this model defines the main factors that affect the strategies of the three stakeholders (as described in Table 1).

According to the model hypotheses, we can create the payoff matrix for the three players in the tourism development game under different decision-making scenarios (as described in Table

2). To minimise the gap between the theoretical model and management practice, it is necessary to define the relationship between related variables. When limiting the number of visitors, updating the infrastructure and balancing community development, ensuring sustainable tourism by limiting the number of tourists is necessary.

Table 2: Payoff Matrix

		Balancing (z)	Unbalancing ($1 - z$)		
		Improving (y)	Unchanging ($1 - y$)	Improving (y)	Unchanging ($1 - y$)
Limiting (x)	Balancing (z)	$B_a - R_{yx} - R_{zx} + A_b + A_c$	$B_a - R_{zx} + A_c$	$B_a - R_{yx} + A_b$	B_a
	Improving (y)	$B_b - R_{xy} - R_{zy} + T$	$-D_b - L$	$B_b - R_{xy}$	$-D_b$
	Unchanging ($1 - y$)	$B_c - R_{xz} - R_{yz} + T$	$B_c - R_{xz}$	$-D_c$	$-D_c$
Unrestricting ($1 - x$)	Balancing (z)	$A_b + A_c$	A_c	A_b	0
	Improving (y)	$B_b - P_a - R_{zy} + T$	$-D_b - P_a - L$	$B_b - P_a$	$-D_b - P_a$
	Unchanging ($1 - y$)	$B_c - Q_a - R_{yz} + T$	$B_c - Q_a$	$-D_c - Q_a$	$-D_c - Q_a$

5.3 Model analysis

In this evolutionary game model, the information obtained by the three parties is asymmetric. It is evident that the above payoff matrix has no equilibrium solution in the context of pure strategy. The three stakeholders of the game adjust their strategies through learning and trials. The values of x , y and z gradually vary, and we can determine the equilibrium solution in a hybrid sense.[4]

Because of information asymmetry, the stakeholders can determine their strategies only by historical experience and thus dynamically adjusting the values of x , y and z . This is manifested as dynamic replication, which is described in the evolutionary game theory as a direct description of the evolutionary process. More generally, to signify the role of a specific strategy in the game, this model assumes that the relative rate of change in the frequency of adopting a specific strategy is directly proportional to the difference of the expected value of the specific strategy and the average expected value of the hybrid strategy. **Then the generated differential equation in the evolutionary game is a replicator dynamics equation**, which can be employed to describe the strategy evolution process in the trilateral game.

This model assumes the following:

- The probability of limiting the number of visitors is x , and that of the opposite is $1 - x$
- The probability of improving infrastructure is y , and the probability of unchanging is $1 - y$

- The probability of balancing community development is z , and the probability of unbalancing community development is $1 - z$; Note that $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$.

According to the analysis above, we can calculate the expected benefits and construct the replicator dynamics equation for decision making.

5.3.1 Strategy stability analysis of Policy I

This model assumes that the expected benefit of local government from limiting the number of visitors is U_{11} , that from loosing the limit is U_{12} , and their average benefit is \bar{U}_1 . Then, Eq. (19) can be obtained.

$$\begin{cases} U_{11} = z[y(B_a - R_{yx} - R_{zx} + A_b + A_c) + (1 - y)(B_a - R_{zx} + A_c)] + (1 - z)[y(B_a - R_{yx} + A_b) + (1 - y)B_a] \\ u_{12} = zy(A_b + A_c) + z(1 - y)A_c + (1 - z)yA_b \\ \bar{U}_1 = xU_{11} + (1 - x)U_{12} \end{cases} \quad (19)$$

Based on Eq. (19), we construct the following replicator dynamics equation (Eq. (20)) for local government's limitation.

$$\alpha(x) = \frac{dx}{dt} = x(\bar{U}_1 - U_{11}) = x(1 - x)(B_a - yR_{yx} - zR_{zx}) \quad (20)$$

According to the stability principle of replicator dynamic equations, to ensure the stability of strategies, x should meet the condition: when $\alpha(x) = 0$, $\alpha'(x) < 0$. We can have the solution as Eq. (21)

$$z = \frac{B_a - R_{yx}y}{R_{zx}} \quad (21)$$

5.3.2 Strategy stability analysis of Policy II

This model assumes that the expected benefit of tourism bureau from improving infrastructure is U_{21} , that from unchanging is U_{22} , and their average benefit is \bar{U}_2 . Then, Eq. (22) can be obtained.

$$\begin{cases} U_{21} = x[z(B_b - R_{xy} - R_{zy} + T) + (1 - z)(B_b - R_{xy})] \\ \quad + (1 - x)[z(B_b - P_a - R_{zy} + T) + (1 - z)(B_a - P_a)] \\ U_{22} = x[z(-D_b - L) + (1 - z)(-D_b)] + (1 - x)[z(-D_b - P_a - L) + (1 - z)(-D_b - P_a)] \\ \bar{U}_2 = yU_{21} + (1 - y)U_{22} \end{cases} \quad (22)$$

Based on Eq. (22), we construct the following replicator dynamics equation (Eq. (23)) for tourism bureau's improvement.

$$\beta(y) = \frac{dy}{dt} = y(U_{21} - \bar{U}_2) = y(1-y)[B_b + D_b + z(T - R_{zy} + L) - xR_{xy}] \quad (23)$$

According to the stability principle of replicator dynamic equations, to ensure the stability of strategies, y should meet the condition: when $\beta(y) = 0, \beta'(y) < 0$. We can have the solution as Eq. (24)

$$x = \frac{B_b + D_b + (T - R_{zy} + L)z}{R_{xy}} \quad (24)$$

5.3.3 Strategy stability analysis of Policy III

This model assumes that the expected benefit of residents from balancing community development is U_{31} , that from unbalancing is U_{32} , and their average benefit is \bar{U}_3 . Then, Eq. (25) can be obtained.

$$\begin{cases} U_{31} = y[x(B_c - R_{xz} - R_{yz} + T) + (1-x)(B_c - Q_a - R_{yz} + T)] \\ \quad + (1-y)[x(B_c - R_{xz}) + (1-x)(B_c - Q_a)] \\ U_{32} = -xyD_c - x(1-y)D_c + (1-x)y(-D_c - Q_a) + (1-x)(1-y)(-D_c - Q_a) \\ \bar{U}_3 = zU_{31} + (1-z)U_{32} \end{cases} \quad (25)$$

Based on Eq. (25), we construct the following replicator dynamics equation (Eq. (26)) for residents' balancing.

$$\gamma(z) = \frac{dz}{dt} = z(U_{31} - \bar{U}_3) = z(1-z)[B_c + D_c - xR_{xz} + y(T - R_{yz})] \quad (26)$$

According to the stability principle of replicator dynamic equations, to ensure the stability of strategies, z should meet the condition: when $\gamma(z) = 0, \gamma'(z) < 0$. We can have the solution as Eq. (27)

$$y = \frac{B_c + D_c - R_{xz}x}{R_{yz} - T} \quad (27)$$

5.3.4 Evolution-stable Strategy analysis

To determine the equilibrium solution to the trilateral game, the simultaneous replicator dynamics equations are created as Eq. (28). There is **only one non-trivial equilibrium solution** $S(x^*, y^*, z^*)$ that meets Eq. (29). So we can make the decision to implement the policy combination follow the guidance of (x^*, y^*, z^*) de-abstracting to X, Y, Z meeting the expenditures constraint Eq. (18).

$$\begin{cases} \alpha(x) = \frac{dx}{dt} = x(U_{11} - \bar{U}_1) = x(1-x)(B_a - yR_{yx} - zR_{zx}) = 0 \\ \beta(y) = \frac{dy}{dt} = y(U_{21} - \bar{U}_2) = y(1-y)[B_b + D_b + z(T - R_{zy} + L) - xR_{xy}] = 0 \\ \gamma(z) = \frac{dz}{dt} = z(U_{31} - \bar{U}_3) = z(1-z)[B_c + D_c - xR_{xz} + y(T - R_{yz})] = 0 \end{cases} \quad (28)$$

$$\begin{cases} x^*(1-x^*)(B_a - y^*R_{yx} - z^*R_{zx}) = 0 \\ [B_b + D_b + z^*(T - R_{zy} + L) - x^*R_{xy}] = 0 \\ [B_c + D_c - x^*R_{xz} + y^*(T - R_{yz})] = 0 \end{cases} \quad (29)$$

6 Case Study: Venice City

We choose Venice, Italy as the city for case study and model migration because it is a typical city where the quality of urban life and the quality of the environment are closely related. With a rising influx of tourists, Venice's urban landscape, notably its intertwining waterways, is bearing the brunt of over-tourism. The impacts of over-tourism in Venice are rather typical, manifesting in the pollution of its water bodies, a decline in the living standards of its residents, and a relentless surge in housing costs, heightening the stress of residential life.

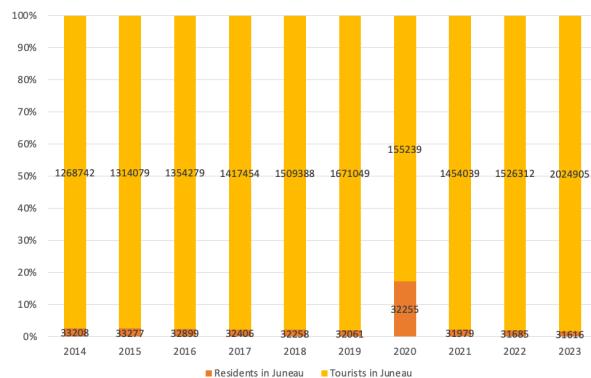


Figure 15: Ratio between Juneau residents and tourists per year

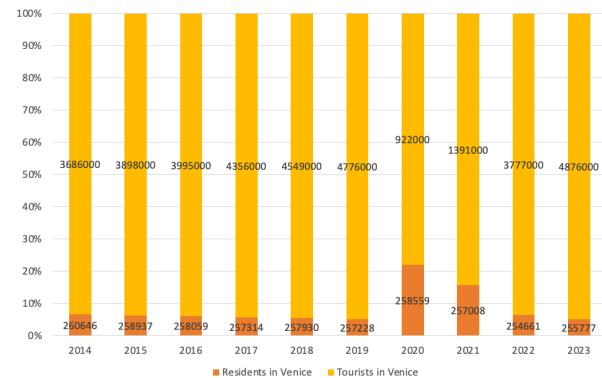


Figure 16: Ratio between Venice residents and tourists per year

6.1 Model Migration

Although there are similar core issues—over-tourism leading to inconvenience for residents and environmental pollution—Venice and Juneau have distinct characteristics. Juneau's main attraction is its glaciers, while Venice is renowned for its unique water-based transportation system, rich historical and cultural heritage, and romantic atmosphere. In Juneau, the focus is on protecting its glaciers; correspondingly, in Venice, the priority is safeguarding its water bodies and historical architecture. Venice is less concerned about carbon emissions but more focused on water pollution. Taking these factors into account, we can adapt Juneau's sustainable development model to Venice by making the following analogies:

- **Glacier Protection in Juneau ↔ Water Body and Historical Building Protection in Venice:**

- Replace the glacier erosion function $G(x_2)$ with a water pollution index or historical building degradation rate tied to tourist activities (e.g., boat traffic, waste disposal).

- **Carbon Emissions in Juneau ↔ Water Pollution in Venice:**

- Replace the carbon footprint function $C(x_0)$ with a water pollution function that accounts for waste, sewage, and boat emissions.

- **Tourist Distribution:**

- Adjust the tourist distribution vector \vec{x} to reflect Venice's unique spatial layout:
 - * x_1 : Tourists in the main city area (e.g., Piazza San Marco).
 - * x_2 : Tourists in popular attractions (e.g., Rialto Bridge, Grand Canal).
 - * x_3 : Tourists in secondary attractions (e.g., Murano, Burano).
 - * x_4 : Tourists in non-tourist areas (residential zones).
 - * x_5 : Overnight tourists in the main city area (high impact on residents).
 - * x_6 : Overnight tourists in secondary areas (e.g., Lido).
 - * x_7 : Overnight tourists in peripheral islands (low impact on residents).

- **Tourism Revenue:**

- Modify the revenue function $R(\vec{x})$ to reflect Venice's income sources:

$$R = Px_2 + Q(x_3 + x_4), \quad P > Q$$

- * P : Revenue from high-end activities (e.g., gondola rides, museum tickets).
- * Q : Revenue from general activities (e.g., island tours).

- **Environmental Constraints:**

- Replace glacier erosion constraints with **water pollution thresholds** and **historical building degradation limits**:

$$G(x_2) = \frac{k_g x_2}{G_{\max}}, \quad C(x_0) = \frac{k_c x_0}{C_{\max}}$$

- * $G(x_2)$: Water pollution index tied to boat traffic.
- * $C(x_0)$: Historical building degradation tied to tourist footfall.

- **Infrastructure Pressure:**

- Adjust infrastructure pressure $F(x_0)$ to account for Venice's water-based transport and fragile architecture:

$$F(x_0) = \alpha x_0$$

* α : Pressure coefficient per tourist (e.g., on vaporettos, walkways).

- **Social Well-being:**

- Modify the social well-being function W to reflect Venice's unique challenges:
 - * w_1 : Resident burden linked to rising rents and overcrowding.
 - * w_2 : Infrastructure occupancy based on water transport and pedestrian traffic.
 - * w_3 : Resident satisfaction that declines with overcrowding.
 - * w_4 : Tourist satisfaction depending on attraction accessibility and quality.

- **Policy Integration:**

- Incorporate Venice's existing policies (e.g., tourist entry fees, boat traffic regulations) into the model to ensure feasibility.

6.2 The effect of location

Different cities face distinct environmental challenges and tourism's invisible burdens, with the severity of over-tourism varying by location. The main attractions also change with location. That's how the choice of location effect which measures will be most important.

6.3 Promote less popular attractions

As shown in the chart of net profit and the number of visitors to the main attraction (glacier) drawn using the model of Juneau, when there are more visitors, our model does not encourage everyone to go to the most popular scenic spots. The proportion of maximum net profit is that some people go to the popular scenic spots and some do not. There are two reasons for this. First, the environmental protection restrictions in the model will reduce the net profit when the number of people in the popular scenic spots is too large. Second, when the scenic spots are too crowded, the satisfaction of visitors will also decrease, thereby reducing the net profit. Thus, our model promotes attractions with fewer tourists to help develop a better balance.

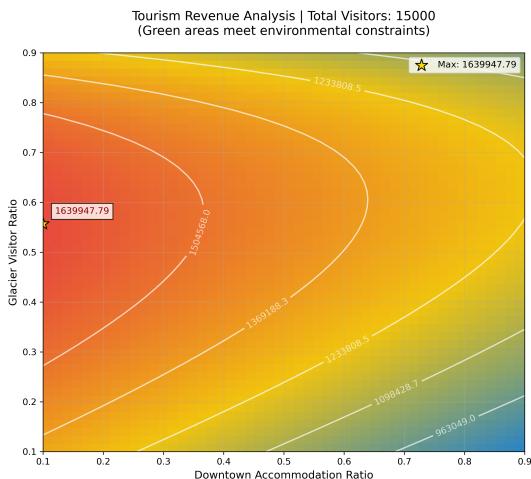


Figure 17: Tourist number = 15000

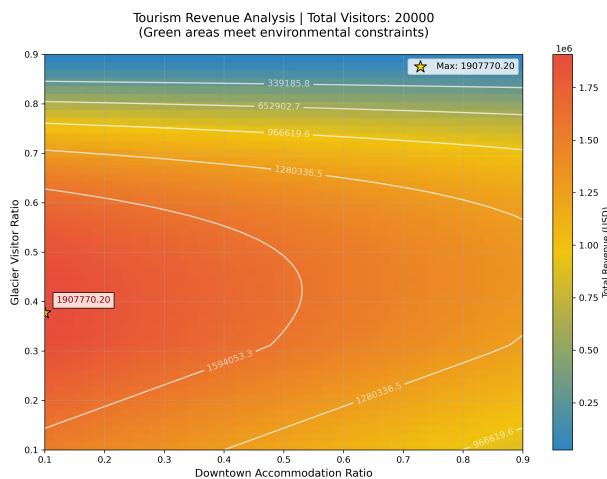


Figure 18: Tourist number = 20000

7 Sensitivity analysis

For the RMM model, set under the condition of the number of tourists in 2023, while the parameter space is selected near the default parameters, the sensitivity of parameters $c_1, c_2, c_3, c_4, y_2, y_3, y_4, D, a, k_g, G_{max}, k_c, kI, C_{max}$ is analyzed. In order to highlight the global stability of some parameters and the trend of the remaining parameters, the floating range of each parameter is set to 20%.

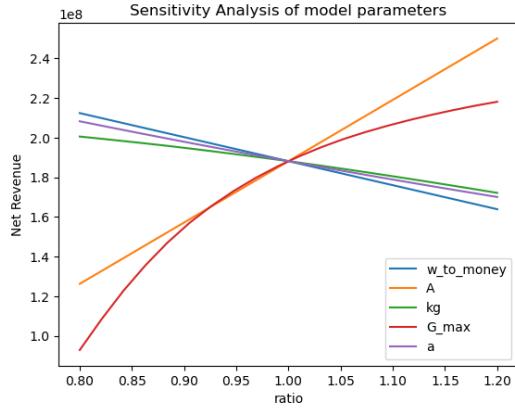


Figure 19: Sensitivity analysis of the top-5 sensitive parameters

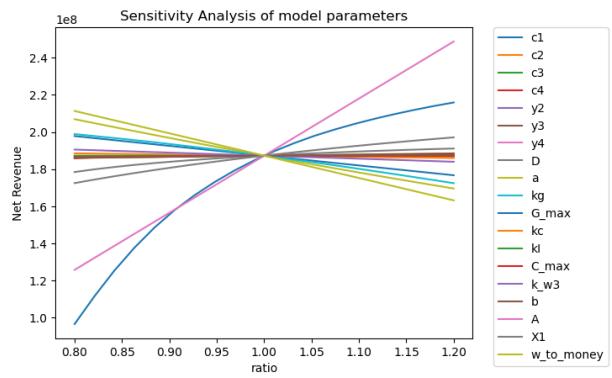


Figure 20: Sensitivity analysis of all parameters

From the sensitivity analysis above, it can be obtained that the model remains stable under the vast majority of parameter floats, while the parameters A, a, X, G_{max}, k_g have large sensitivities, implying that they have a significant impact on the optimization objective N . k_g implies per capita glacier ablation from tourists, while A represents per capita consumption by tourists, and a is a built-in parameter for environmental limiting factors.

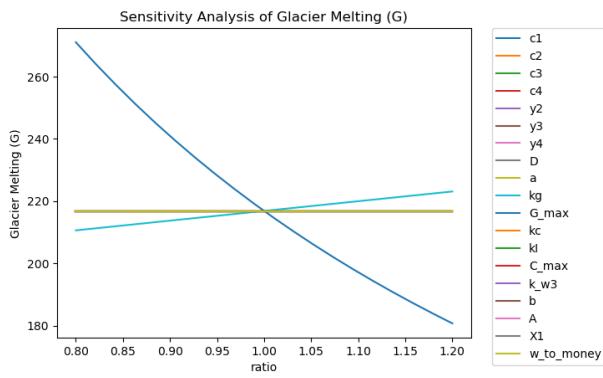


Figure 21: Sensitivity analysis of all parameters related to G

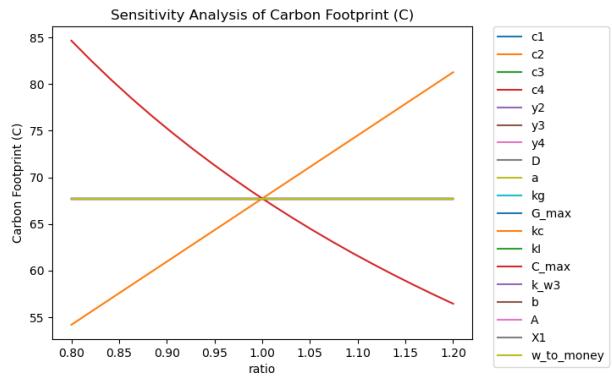


Figure 22: Sensitivity analysis of all parameters related to C

From the sensitivity analysis of the glacier ablation index G and carbon emission index C model, the model is mainly determined by the per capita contribution of tourists and the normalization factor, which is also consistent with the reality.

To sum up, the sensitivity of these parameters offers valuable insights for policy-making. From these analysis we can see that implementing reasonable limits on glacier tourist numbers, reducing carbon emissions from tourism activities, and optimizing tourists' consumption patterns can significantly contribute to maintaining a sustainable and profitable tourism industry.

8 Strengths and weaknesses

8.1 Strengths

- By utilizing evolutionary game theory to examine the relationship between policies, the study has attained a comprehensive implicit function solution. It also possesses strong generalizability, allowing for parameter adjustments based on the specific context of the subject.
- By connecting residents, tourists, and municipal bodies through a social welfare function, the framework has established a dependable indicator for evaluating the overall benefits of sustainable tourism industry.
- The model's environmental constraint variables, characterized by their continuity, offer a more precise representation of environmental dynamics within sustainable tourism development compared to traditional environmental assessment scores.

8.2 Weaknesses

- Approximation measures such as assuming that the number of arriving cruise ships satisfies a Poisson distribution, and that the number of arrivals per cruise ship is the same were taken in the optimization to ensure convergence.
- The weighting coefficients of the social welfare function are abstract and therefore difficult to optimize by empirical analysis.
- The selection for the constraints is more abbreviated, with the upper and lower bound restrictions being the main ones.

Memo

*To: Tourist Council of Juneau
From: Team #2501702, MCM2025
Subject:
Date: January 27, 2025*

Dear Officer of the Juneau Tourist Council,

It is our honor to present to you our proposal on sustainable tourism in the city of Juneau. Through a careful study of the city, we have proposed the RMM optimization model. Given the situation of the city of Juneau, we are now proposing the RMM-PF model to outline various measures and advice on how to optimize the outcome of sustainable policies.

We present to you the prediction and advice in the following 3 points:

- There is no doubt that the Mendenhall Glacier is an invaluable asset to the city of Juneau, but it is melting at an increasing rate due to over-development of the tourism industry, which has resulted in large numbers of tourists trampling on the covering snow and thus altering its reflectivity. Our model predicts that limiting glacier visitation to approximately 50% of the total number of visitors will maximize the combined benefits when the number of visitors is around the average of that in the peak season.
- Our model also has good predictions for lodging diversions in urban areas. Firstly for the main urban area, when the scale of tourists is small, i.e. off-season, the accommodation rates in the main urban area can be adjusted by appropriate pricing policies. As a result, more tourists can be attracted to the main urban area, which has relatively higher spending and more convenient transportation, thus increasing the comprehensive income. Additionally, the impact of the infrastructure on the comprehensive income will be greatly reduced as the demand for infrastructure by tourists in the off-season is within the controllable range.
- For the peak tourist season, sub-urban areas should be better developed in sustainable tourism. Our model gives the prediction that the main urban area can only handle a limited number of tourists in the peak season. So when the number of the tourists is indeed large, the tourists need to be attracted to stay in the sub-city through promotional guidance or pricing policies. In order to maintain the overall satisfaction of tourists, special transportation routes to attractions can also be introduced, thus optimizing Juneau's overall benefits.

We anticipate engaging in further dialogues with you and the community to secure the enduring preservation of Juneau's magnificent landscapes, ensuring they stand as cherished landmarks for centuries to come.

Thank you for your attention and consideration!

Sincerely,

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Report on Use of AI

1. OpenAI gpt 4o mini

Query1:

Currently, there is a survey on social welfare in Juneau, which considers four indicators: resident burden (composed of housing supply and costs, crowding, and stress caused by noisy tourists), resident infrastructure occupancy rate, resident satisfaction, and tourist satisfaction. Each indicator is determined by a continuous score between 1-5. We aim to comprehensively evaluate the social welfare of Juneau based on these four indicators (let's represent these indicators as w1, w2, w3, and w4). The survey asks respondents to rate the contribution of each indicator to social welfare with integers between 1-100 (with a minimum score of 1 and a maximum score of 100, all being integer scores).

Now, assume you are 100 highly professional sociologists, analysts, and social assessors who have filled out these 100 surveys. Please provide a table with the survey results. This table should have 100 rows and 4 columns of scores, where each score is an integer between 1-100. (Note: You are now 100 highly professional sociologists, analysts, and social assessors; please analyze and score carefully rather than providing a table containing 400 random numbers.)

Output1: When designing a survey scoring table for the social welfare of Juneau, we need to deeply understand the significance of each indicator and their interrelationships, and conduct reasonable analysis and scoring with a scientific and rigorous attitude. Below is an in-depth analysis of the four indicators, the basis for scoring, and the final table.

1. **Core Issues Analysis**

The central question we face is how to comprehensively assess Juneau's social welfare and derive an overall evaluation through four key indicators (resident burden, infrastructure occupancy rate, resident satisfaction, tourist satisfaction). Each indicator has different influencing factors and interrelationships that must be analyzed in detail.

2. **Exploring Causes and Consequences**

- ****Resident Burden (w1)**:** With the increase in tourist numbers, the pressure on housing supply and costs rises, leading to a higher cost of living for residents. This directly affects residents' economic burden, quality of life, and happiness.

- ****Infrastructure Occupancy Rate (w2)**:** The availability and quality of infrastructure (such as public transport, healthcare, education, etc.) can be impacted by the influx of tourists, thus affecting residents' daily lives.
- ****Resident Satisfaction (w3)**:** This measures residents' perceptions of the quality of their living environment, encompassing various aspects such as economic, social, and environmental factors. If residents feel an increased burden, their satisfaction will decline.
- ****Tourist Satisfaction (w4)**:** The quality of tourist experiences directly affects the sustainability of tourism revenue. If tourists decide not to choose Juneau due to congestion and environmental degradation, it will negatively affect the economy.

3. ****Related Previous Work and Supporting Evidence****

Existing studies indicate that rapid tourism development often accompanies increased environmental and social costs: - ****Environmental Research**:** Some studies have found that tourism activities exacerbate pressure on ecosystems, leading to resource depletion and ecological degradation (as exemplified by Mendenhall Glacier).

- ****Social Factors**:** Surveys show that high volumes of tourists lead to local residents' dissatisfaction with their quality of life, thereby affecting family stability and community harmony.

4. ****In-Depth Consideration and Discussion****

Through analyzing these factors, we can think more deeply about how to formulate policies to balance economic benefits with social costs. This involves finding a balance between attracting tourists and protecting the quality of life of local residents. Subsequent questions include: - How can tourist flow be effectively managed to mitigate impacts on residents? - What support policies can help improve infrastructure and alleviate residents' burdens?

5. ****Specific Responses and Actual Replies****

Based on the above analysis and considerations, the scores provided by 100 professional sociologists and analysts are as follows:

w_1	w_1	w_3	w_4	w_1	w_1	w_3	w_4
45	60	55	75	71	73	58	79
65	50	60	80	74	72	61	74
70	65	70	85	67	66	65	82
55	55	65	70	31	49	55	66
50	58	50	78	62	50	52	70
60	75	74	82	33	80	75	90
40	48	54	68	42	55	68	73
58	62	73	79	39	67	63	76
67	70	76	81	77	77	80	89
72	60	62	74	56	83	70	85
30	47	52	64	53	91	92	94
51	68	78	86	66	54	62	80
41	52	50	72	72	68	74	90
66	55	66	88	57	43	48	58
48	69	63	69	69	73	75	85
55	85	75	93	34	59	65	80
63	45	71	84	43	74	73	75
35	61	59	76	75	82	81	88
78	67	81	90	62	64	66	72
59	72	80	77	39	56	59	77
40	53	56	69	60	55	65	79
53	82	74	75	30	68	63	69
66	60	62	80	50	78	70	80
64	66	65	82	65	54	54	72
58	68	70	73	78	50	62	83
47	45	52	75	40	62	69	74
72	79	78	88	88	90	76	89
55	50	66	71	60	46	57	69
73	57	53	69	85	84	73	81
37	72	81	90	41	72	71	76
80	88	85	92	75	85	78	82
65	54	49	78	68	48	68	77
50	65	72	66	71	88	66	88
45	79	67	77	66	77	74	80
76	54	82	88	54	70	63	66
88	48	62	63	38	43	55	60
83	90	70	91	82	66	81	90
61	59	72	85	61	41	59	78
70	76	77	94	62	49	72	84
54	53	60	64	44	69	64	73
52	69	64	80	46	65	77	90
66	67	66	78	91	76	88	92
68	55	83	91	57	81	70	85
59	82	71	87	58	62	56	72

Conclusion

This result table, based on the analyses of professional sociologists, reflects a multidimensional assessment of social welfare in Juneau. It can serve as a foundation for further policy formulation and community planning, helping decision-makers to consider the quality of life for residents while promoting sustainable tourism development. If you need further analysis or application of these data, please feel free to let me know.

2. Some of the paragraphs were polished using GPT-3.5 turbo, but all uses on AI were used under the supervision of team members.