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B		2509436

Sustainable Tourism Modeling: Multi-Objective Balancing in Juneau and Hawaii

Summary

Juneau, Alaska, is a famous tourist city. Tourism brings a lot of revenue to the city, but at the same time, the problem of overtourism has also hit. The Mendenhall Glacier is receding and local residents are under pressure from higher housing costs and overcrowding.

In order to solve these problems and develop sustainable tourism, this paper constructs a comprehensive **multi-objective optimization model** to evaluate the impact of various aspects of overtourism on cities.

For Problem 1, we developed a **Multi-Objective Optimization Model** with annual tourist volume as the decision variable. Objectives include maximizing **tourism revenue**, **minimizing infrastructure pressure**, **reducing environmental impact**, and maximizing **resident satisfaction**. In order to quantify these aspects, we utilized methods such as **Analytic Hierarchy Process**. The model integrates constraints for each objective via a linear weighted sum method, generating optimal solutions through a composite fitness function. Results indicate that controlled tourist numbers sustain revenue while alleviating infrastructure strain, environmental stress, and improving resident satisfaction. A revenue allocation plan distributes hotel and tourist taxes to infrastructure, environmental protection, and community projects.

Sensitivity analysis shows balanced constraint weights are crucial for maintaining tourism revenue alongside socio-environmental stability. **Enhanced infrastructure**, **environmental measures**, and **resident satisfaction** further increase Juneau's tourist capacity and revenue potential.

For Problem 2, we adapted parameters in the multi-objective optimization model from Problem 1 to Hawaiian conditions, including tourism revenue, infrastructure pressure, environmental pressure, and resident satisfaction functions. The model was **customized for four Hawaiian destinations**: Oahu, Kauai, Maui, and Hawaii Island, yielding four parameter-distinct models. We evaluated optimal solutions and maximum fitness values under three interventions: **altering tourist coral protection rates**, **modifying government employment assistance levels**, and **upgrading infrastructure construction scores**.

To promote less-crowded scenic spots, we developed a **Multi-Attribute Resource Allocation Model** that quantifies relative attractiveness through visitor distribution ratios. The optimal allocation scheme maximizes the total objective function under given tourist volume constraints. Through iterative adjustments of visitor distribution plans and corresponding objective function calculations, the model identifies the best visitor allocation ratios as the relative attractiveness values. Sensitivity analysis demonstrates that adjusting total tourist volume parameters preserves these proportional relationships. Three actionable strategies emerge from parameter modifications: **enhancing infrastructure**, **reducing tourism taxes**, and **implementing visitor caps** at popular attractions.

The paper concludes with an evaluation of the model's **strengths** and **weaknesses**, accompanied by a policy memorandum to the Juneau Tourism Council synthesizing these findings.

Key Words: Multi-Objective Optimization model; Analytic Hierarchy Process; Linear constrains; sustainable tourism; Coral Bleaching; Glacier receding

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1 Introduction

1.1 Problem Background

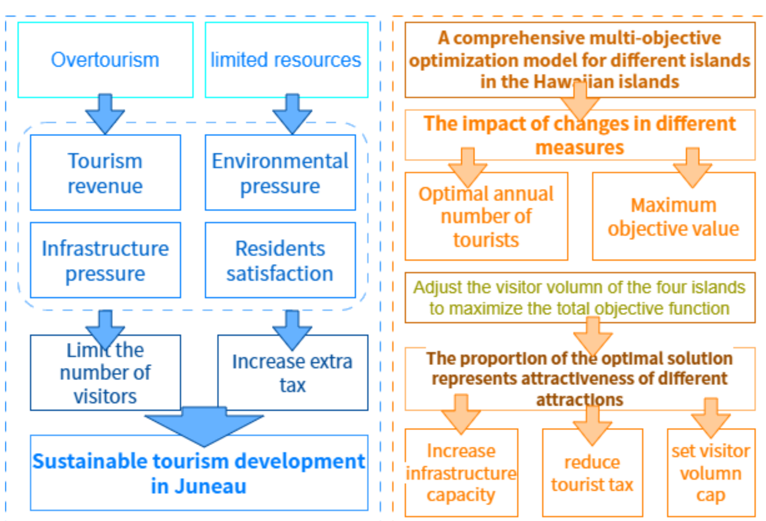
As an important tourist destination in Alaska, the city of Juneau has seen significant growth in visitor numbers in recent years, receiving 1.6 million visitors in 2023 alone. Over tourism has brought problems such as increased pressure on infrastructure, environmental degradation, and decreased satisfaction among residents. The retreat of Mendenhall Glacier, increased pressure on waste disposal, and a rising carbon footprint all reflect the challenges tourism poses to local ecology and communities. We hope to find a sustainable tourism development model that can maintain the tourism economy while striking a balance between environmental protection and social stability.

1.2 Literature Review

- Establish a sustainable tourism model for Juneau that considers the impact of tourism on the economy, society, and natural environment.
- Identify the key factors in this model that need to be optimally implemented for the sustainable development of tourism in Juneau, and discuss which factors are most important.
- Explore how the additional tax on visitors is used to implement measures that affect tourism in Juneau.
- Investigate how this sustainable tourism model can be applied to other over-travelled locations.
- Identify key measures for sustaining tourism in another location.
- Provide the Juneau City Council with improvement measures for tourism based on the sustainable tourism model.

1.3 Our work

Our work is shown in the picture.



2 Preparation of the Models

2.1 Assumptions Justification

Considering that practical problems always contain many complex factors, first of all, we need to make reasonable assumptions to simplify the model, and each hypothesis is closely followed by its corresponding explanation.

- **Assumption 1: The impact of each visitor on society and the environment is assumed to be constant.** Since the differences between individual visitors are difficult to quantify, considering these variations would make our model overly complex.
- **Assumption 2: Assume that tourism-related policies can be effectively implemented, and their effects can be promptly reflected.** This simplifies the potential real-world scenario where policy implementation might be inadequate.
- **Assumption 3: The development status and data of Alaska's tourism industry can, to some extent, represent the tourism-related data of Juneau.** This is because, based on the data[1], Juneau, as the core city of tourism in Alaska, serves as the central pillar of the state's tourism industry.
- **Assumption 4: Assume that the economic, social, and natural environment of the tourist destination will not undergo unforeseen changes in the short term.** Such as large-scale natural disasters, economic crises. Force majeure factors such as COVID-19 have a significant impact on the tourism industry.Therefore, data from 2020 and 2021 have been excluded from our selected dataset.
- **Assumption 5: In Section 4, the visitor volume for Hawaii only includes tourists arriving by air, excluding other modes of transportation.** This is because, according to statistics from the Hawaii Department of Business, Economic Development & Tourism[2], in 2023, over 98% of tourists entered Hawaii by air. Therefore, the number of tourists arriving by other means of transportation is negligible.

2.2 Notations

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

3 Sustainable Tourism Industry Model

The central goal of building a sustainable tourism model for Juneau, Alaska, is to achieve long-term sustainability in tourism while balancing explicit revenue from economic benefits with implicit costs such as infrastructure capacity, environmental protection, and resident satisfaction. We need to consider maximizing urban tourism income while ensuring the stability of the natural ecological environment and social order.

Table 1: Notations

Symbol	Definition
x	total visitor volume
x_i	the visitor volume to the $i-th$ island
R	total revenue
R_{max}	maximum tourism revenue
I	infrastructure pressure
I_{max}	maximum infrastructure capacity
E	environmental pressure
E_{max}	maximum environmental pressure
S	resident satisfaction
S_{max}	maximum resident satisfaction
Z	objective function score
w_i	weight of each indicator
T	temperature
A_i	attractiveness of the $i-th$ island
$Score_i$	infrastructure development score of the i-th location
K	level of employment assistance

3.1 Tourism Industry Revenue Model

The **visitor volume** to Juneau is calculated by summing the number of people arriving by cruise ships and the number of people arriving by air. These two modes of transportation account for over 97% of the visitors to Juneau. Thus, this method provides a reliable estimate of the visitor volume to Juneau.

Based on the current assumptions, we select the more authoritative annual *total visitor-related output of Alaska* as the foundational data for **tourism revenue**. This data can, to some extent, reflect the tourism-related data of Juneau.

Taxes generated from tourist consumption are used for infrastructure development, improving residents' quality of life, and enhancing environmental protection. According to the *COMPILED LAWS OF THE CITY AND BOROUGH OF JUNEAU, ALASKA, VOLUME I*, specifically Section 69.05, the total sales tax rate was **4%** before October 1, 2023, and increased to 5% after that date.

$$c_v = \frac{R_{\text{after}-\text{tax}}}{x} = \frac{R\,(1+t_{\text{tax}})}{x} \tag{1}$$

Here, c_v stands for **per capita consumption**. x stands for **total visitor volume**. R stands for **total revenue**. $R_{\text{after}-\text{tax}}$ stands for **revenue after tax**.

Substituting historical data, we obtain the following per capita consumption values for the respective years:

Table 2: Per capita consumption data

	2008	2011	2013	2014	2015	2017
per capita consumption	\$1739.3	\$2054.5	\$1992.9	\$2018.0	\$2054.5	\$2032.1

Excluding factors such as inflation, we can assume that the per capita consumption by tourists is approximately \$2000 with minor fluctuations. Therefore, we simplify the model by assuming that the **per capita consumption** is **constant**, taking \$2000 as the reference value. Thus:

$$R_{\text{after}-\text{tax}} = \frac{c_v \cdot x}{1 + t_{\text{tax}}} = \frac{2000 \cdot x}{1.04} \tag{2}$$

3.2 Infrastructure Pressure Model

Every year, Juneau receives a large number of tourists. For a city with **only 31,000 residents**, the busiest days can see **up to 20,000 visitors** arriving in Juneau. This undoubtedly places significant pressure on the local infrastructure. To quantify the impact of a large number of tourists on the local infrastructure, we introduce an indicator—Infrastructure Pressure I.

First, since specific data on Juneau's infrastructure is unavailable, we refer to the infrastructure conditions of Alaska to represent the infrastructure level of Juneau. Based on the American Society of Civil Engineers' ratings of various facilities in Alaska, and considering the importance of different infrastructure components, we use the **Analytic Hierarchy Process (AHP)** to quantify Alaska's **infrastructure score**. First, we construct a weight matrix:

Table 3: weight matrix

	Energy & GHG	Water	Solid waste	Wastewater	Ports	Aviation	Road
Energy & GHG	1.0000	2.0000	3.0000	4.0000	5.0000	7.0000	9.0000
Water	0.5000	1.0000	2.0000	3.0000	4.0000	6.0000	8.0000
Solid waste	0.3333	0.5000	1.0000	2.0000	3.0000	5.0000	7.0000
Wastewater	0.2500	0.3333	0.5000	1.0000	2.0000	4.0000	6.0000
Ports	0.2000	0.2500	0.3333	0.5000	1.0000	3.0000	5.0000
Aviation	0.1429	0.1667	0.2000	0.2500	0.3333	1.0000	3.0000
Road	0.1111	0.1250	0.1429	0.1667	0.2000	0.3333	1.0000

The calculated **consistency ratio CR = 0.081 < 0.1**, which meets the consistency requirement. The weights of each component are calculated using the eigenvector method. By comparing **the GPA table**, the grades for the above seven items are translated into specific grades:

Table 4: Weights and scores for each item

	Energy & GHG	Water	Solid waste	Wastewater	Ports	Aviation	Road
weight	0.3544852	0.24182205	0.16189598	0.10813737	0.07354975	0.03818239	0.02192725
rank	C-	D	C	D	D+	C	C
Score	1.7	1.0	2.0	1.0	1.3	2.0	2.0

Based on Table 4, the weighted score for Juneau's local infrastructure is calculated as:

$$\text{Score}_{\text{Juneau\_infra}} = \sum_i (\text{Weight}_i \times \text{Score}_i) = 1.492 \tag{3}$$

Where $Score_{Juneau\_infra}$ represents the infrastructure score in Juneau. We recognize that the local infrastructure is shared by both residents and visitors, and therefore we have established the following formula:

$$I = \frac{P_{\text{local}} + x \cdot \frac{X_{\text{daily\_max}}}{X_{\text{annual}}}}{\text{Score}_{\text{Juneau\_infra}}} \tag{4}$$

where $\frac{X_{\text{daily\_max}}}{X_{\text{annual}}}$ represents **the ratio of the highest daily number of visitors in 2023 to the annual number of visitors in 2023**, indicating the day with the maximum infrastructure pressure under a given annual number of visitors. Here, P_{local} is **the number of local residents**, and P_{max} is **the maximum number of visitors** that Juneau can accommodate.

3.3 Environmental Pressure Model

Mendenhall Glacier, as a popular attraction in Juneau, has seen an increase in greenhouse gas emissions as more visitors come to the town. For a glacier, this is undoubtedly catastrophic, leading to the **continuous retreat and decline of the Mendenhall Glacier**. We aim to use **the annual melting area of this glacier and the nearby glacial system, the Juneau Icefield**, as an indicator to measure the environmental pressure index $E(x)$ caused by the surge in tourist numbers.

The rate of glacier retreat is influenced by the global warming trend and the temperature in the region. In the case of global warming, even without additional greenhouse gas emissions, glaciers would still experience some degree of melting. According to the empirical formula, **the melting rate of glaciers** can be expressed in the following form:

$$E = a + K_{E1}(T - T_{\text{melt}})^4 \tag{5}$$

where: a represents **the initial melting rate of the glacier**, T is **the current temperature**, usually expressed in degrees Celsius, T_{melt} is **the melting point temperature of ice**, typically 0°C. k_{E1} represents **the degree of influence of temperature on the melting rate**.

As a popular tourist area, the temperature rise in the Mendenhall Glacier region is primarily caused by carbon emissions. According to the formula from **the IPCC report**[4], we can understand that the local temperature increase has a logarithmic relationship with greenhouse gas emissions from human activities, specifically carbon emissions:

$$\Delta T = K_{E2}\alpha \log(0.01 * E + 1) \tag{6}$$

Thus, the relationship between regional temperature T and carbon emissions E can be expressed as:

$$(T - T_{\text{melt}})^4 = \Delta T = K_{E2}\alpha \log(0.01 * E + 1) \tag{7}$$

From Zhang's research on per capita carbon emissions[5], it is proposed that in developed countries, the relationship between tourist numbers and carbon emissions is approximately 665.4 kg per person. Further, we can derive **the annual glacier melting rate** as:

$$E = a + K_{E1}(K_{E2}\alpha \log(0.01 * N * 0.6654 + 1))^4 \tag{8}$$

where N is the annual number of tourists, in units of ten thousand people.

At the same time, by incorporating the visitor numbers in Juneau and the melting area of the Juneau Icefield for the years 2015, 2019, and 2023, we fit the curve data and obtain the coefficients: a = 7, $K_{E1} = 6$, $K_{E2} = 4$.

3.4 Resident Satisfaction Model

In recent years, the rapid expansion of the tourism industry has caused significant disruptions to the daily lives of local residents in Juneau. Issues such as "Vehicle congestion downtown," "Flight-seeing noise," and "Air emissions from cruise ships" have emerged as major concerns. To quantitatively study the impact of tourism on Juneau's local residents, we introduce an indicator—**resident satisfaction** S.

According to the papers *Unemployment and life satisfaction: a non-linear adaptation process* and *The Correlation Between Cultural Tourism Motivation and Tourism Tolerance*[10], resident satisfaction is influenced by the local unemployment rate. Additionally, in cities like Juneau that are heavily affected by tourism, resident satisfaction is also related to the visitor volume.

Specifically, **resident satisfaction** S has a **linear** relationship with the **employment rate** r_{employ} and an **exponential decay** relationship with **visitor volume** x. This can be expressed as:

$$S = K_{S0} + K_{S1} \cdot r_{\text{employ}} + K_{S2} \cdot e^{K_{S3} \cdot x} \tag{9}$$

or equivalently:

$$S = K_{S0} + K_{S1} \cdot \left(1 - r_{\text{unemploy}}\right) + K_{S2} \cdot e^{K_{S3} \cdot x} \tag{10}$$

where K_{S0} represents the **baseline satisfaction**, and r_{unemploy} is the **unemployment rate**.

To further refine the model, based on the paper *Tourism and contribution to employment: global evidence*[11], we note that there is an **exponential decay** relationship between the **unemployment rate** and **visitor volume**. Thus, **resident satisfaction** can be refined as:

$$S = K_{S0} + K_{S1} \cdot \left(1 - ae^{bx}\right) + K_{S2} \cdot e^{K_{S3} \cdot x} \tag{11}$$

where a and b are coefficients representing the relationship between the **unemployment rate** and **visitor volume**. These coefficients are derived from fitting the unemployment rate and annual visitor volume data for Juneau from 2008 to 2017:

$$a = 0.2413, \quad b = -7.974 \times 10^{-3}$$

- The **baseline satisfaction** K_{S0} is set to 0.5.

- The coefficients K_{S1}, K_{S2}, and K_{S3} are adjusted based on Juneau's resident satisfaction surveys and the corresponding visitor volume data to ensure that the resident satisfaction S aligns with real-world observations.

  For Juneau, the coefficients are set to the following values:

$$K_{S1} = 5, \quad K_{S2} = 10, \quad K_{S3} = -4 \times 10^{-8}$$

3.5 Establishment of a Comprehensive Multi-Objective Optimization Model

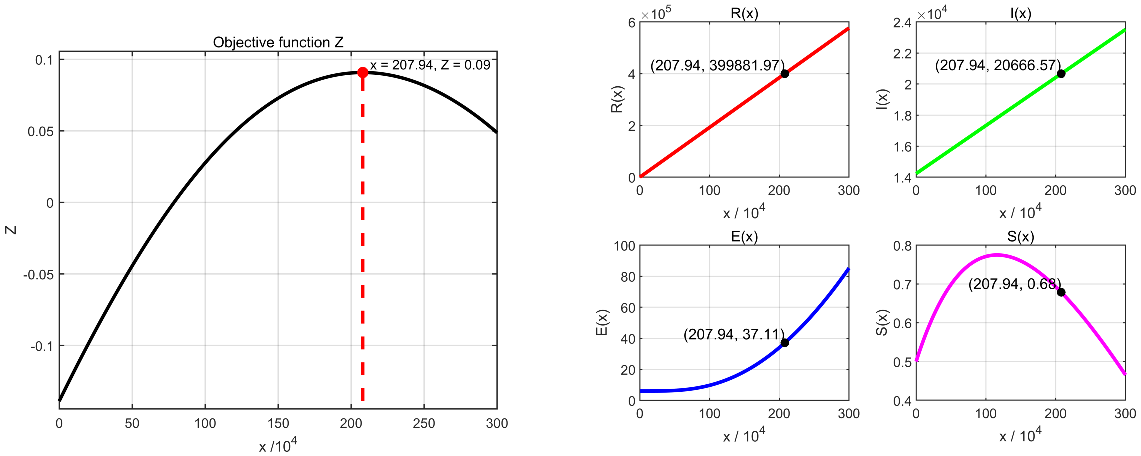
In the previous sections, we have successfully established the relationships between **annual tourist numbers and tourism revenue** R**, infrastructure pressure** I**, environmental pressure** E**, and resident satisfaction** S. To further develop our model, we introduce constraints for the four optimization objectives as follows:

- $R_{\max}$: Represents **the maximum tourism revenue for Juneau**. Calculated based on the tourism revenue when the annual number of tourists reaches 3 million, assuming constant spending per tourist.
- $I_{\max}$: Represents **the maximum infrastructure capacity of Juneau**. Determined by the local resident population P_{local} plus the maximum daily tourist number of 30,000.
- $E_{\max}$: Represents **the acceptable maximum annual melting rate of the Juneau Icefield**. Set at 60 square kilometers per year, which is approximately twice the current melting rate.
- $S_{\max}$: Represents **the maximum resident satisfaction**. Set at 100%, or 1.

In order to construct a multi-objective optimization problem, we first need to normalize all the four indicators, eliminate the two gaps between them, and give **the weight coefficients** $w_1 + w_2 + w_3 + w_4 = 1$ to balance the priority among them, so we get the formula of **the objective function Z**:

$$Z(x) = w_1 \cdot \left(\frac{R(x)}{R_{\max}}\right) - w_2 \cdot \left(\frac{I(x)}{I_{\max}}\right) - w_3 \cdot \left(\frac{E(x)}{E_{\max}}\right) - w_4 \cdot (1 - S(x)) \tag{12}$$

For the four weights, we set them as follows: The four weights are set as follows: $\mathbf{w_1 = 0.5}$ indicates that tourism revenue dominates in this model, making economic benefit the primary optimization objective. $\mathbf{w_2 = 0.2}$ and $\mathbf{w_3 = 0.2}$ correspond to infrastructure pressure and environmental pressure, respectively, emphasizing that while pursuing economic benefits, it is also crucial to consider the city's infrastructure capacity and ecological protection to prevent resource depletion or environmental degradation caused by overdevelopment. Finally, $\mathbf{w_4 = 0.1}$ represents resident satisfaction, indicating that a certain level of resident happiness must be maintained, although its priority is relatively low and it mainly serves as an auxiliary constraint.



(a) Objection Function Z

(b) Evaluation Metrics

Figure 1: Model result

Under these weights, as shown in Figure 1a, we calculate that when the objective function Z is maximized, the optimal annual number of tourists is **2.0794 million**. At this point, as observed in Figure 1b, the tourism revenue $R(x)$ is **$390 million**, the maximum daily number of tourists is **20,600**, the glacial melting rate is **37.11 square kilometers per year**, and the resident satisfaction rate is **68%**. All these values fall within a reasonable range, demonstrating that the model achieves a balance between ensuring tourism revenue and maintaining social and environmental stability, thereby validating the correctness of the model.

3.6 Additional Revenue Expenditure Plan

After determining the model structure, we formulated **an additional income expenditure plan** aimed at promoting the development of sustainable tourism by rationally allocating the additional income generated by tourism. We allocate this additional income proportionally to three key areas: **infrastructure improvement, environmental protection, and community development.**

First, in terms of **infrastructure improvement**, we allocate a portion of the income $w_1 \cdot R(x)$ to the construction and upgrading of infrastructure in various aspects, such as water supply and drainage systems, transportation road facilities, and more. By building and expanding transportation roads, we reduce **the burden on the transportation system caused by tourists**, thereby alleviating traffic congestion and emissions, lowering the infrastructure pressure index $I(x)$, and **enhancing the transportation system's capacity** to accommodate both tourists and residents.

Second, in terms of **environmental protection**, we allocate a portion of the income $w_2 \cdot R(x)$ to critical ecological protection projects, such as glacier conservation and forest ecosystem restoration, to slow down the rate of environmental degradation. Taking glacier conservation as an example, by **investing in scientific monitoring and ecological restoration projects**, we can not only **reduce the rate of glacial retreat** but also **lower the environmental impact index** $E(x)$. This helps protect the unique natural ice landscapes, maintain ecological balance, and ensure the sustainable use of tourism resources.

Finally, in terms of **community development**, a portion of the income $w_3 \cdot R(x)$ will be used to

enhance local residents' employment skills training and the construction of community public facilities. By providing skills training, residents can gain **more employment opportunities and increase their income**. At the same time, improving the living environment enhances resident satisfaction $S(x)$, promoting stable socio-economic growth.

Through this rational allocation of income, we can not only **enhance the carrying capacity of tourism** but also **achieve the dual goals of environmental protection and community development**, driving the long-term development of sustainable tourism.

3.7 Sensitivity Analysis

3.7.1 Sensitivity Analysis of Weights

The objective function(12) in the model involves the weights w_1, w_2, w_3, and w_4 for tourism revenue, infrastructure pressure, environmental pressure, and resident satisfaction, respectively, with $w_1 + w_2 + w_3 + w_4 = 1$. For the four weight parameters, we first fix the other weights and independently vary w_1 **from 0.05 to 0.95 in increments of 0.05**.

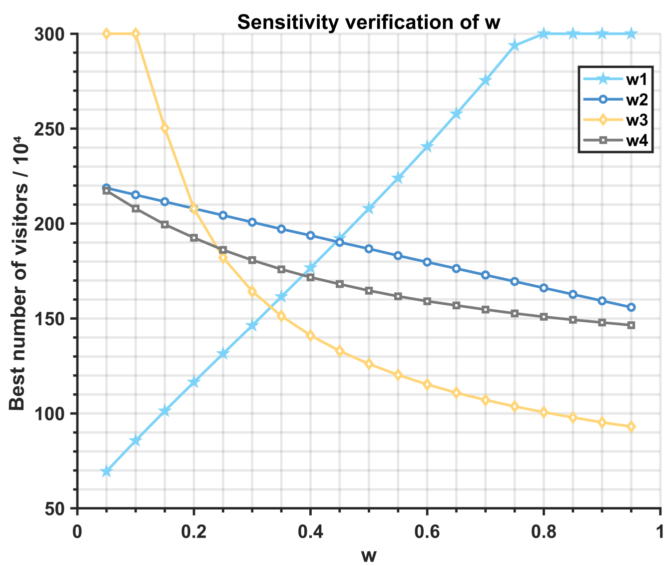


Figure 2: Sensitivity Analysis of Weights

When w_1, w_2, w_3, and w_4 change, the optimal annual number of tourists responds as follows:

- **Tourist income weight** (w_1): The optimal annual number of tourists increases linearly as w_1 increases. Starting from 2.1875 million ($w_1 = 0.05$), it reaches the maximum limit of 3 million when $w_1 = 0.8$. This indicates that **when policies prioritize tourist income, the model attracts more tourists to maximize revenue**.
- **Infrastructure pressure weight** (w_2): From 2.1875 million ($w_2 = 0.05$) to 1.559 million ($w_2 = 0.95$), the model tends to **reduce the number of tourists to ease the burden when policies emphasize infrastructure pressure**.

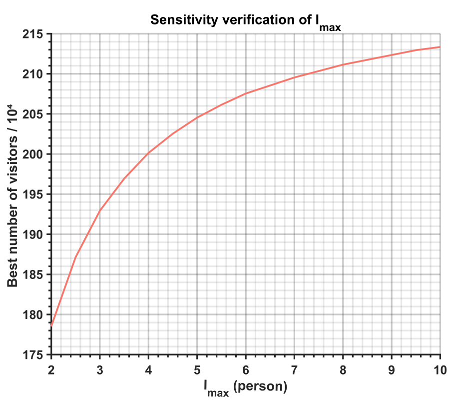
- **Environmental pressure weight** (w_3): A rapid decline is observed, from 3 million ($w_3 = 0.05$) to 930,600 ($w_3 = 0.95$), indicating that **when environmental pressures are valued by policies, the model significantly reduces the number of tourists to protect the glacial environment**.

- **Resident satisfaction weight** (w_4): The number of tourists decreases rapidly from 2.1735 million ($w_4 = 0.05$) to 1.465 million ($w_4 = 0.95$), indicating that **when policies prioritize residents' happiness, the model tends to reduce the number of tourists to alleviate social problems**.

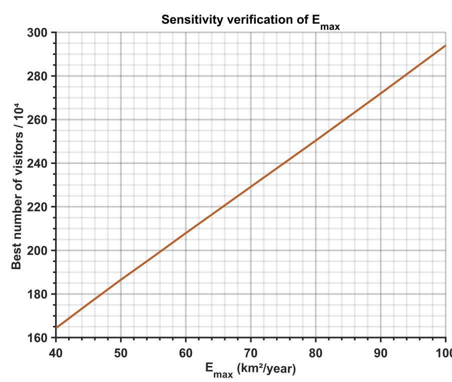
Through sensitivity analysis, we independently adjusted each weight (w_1, w_2, w_3, w_4) while keeping the others fixed, obtaining the optimal results for different numbers of tourists. The analysis shows that **policies need to balance maintaining tourism revenue with managing infrastructure pressure, environmental damage, and the impact on local residents' lives caused by excessive tourism**.

3.7.2 Sensitivity Analysis of Parameters

We keep w_1, w_2, w_3, w_4 fixed at the initial values set in the model and adjust various parameters to observe changes in the optimal annual number of tourists.



(a) Change I_{max}

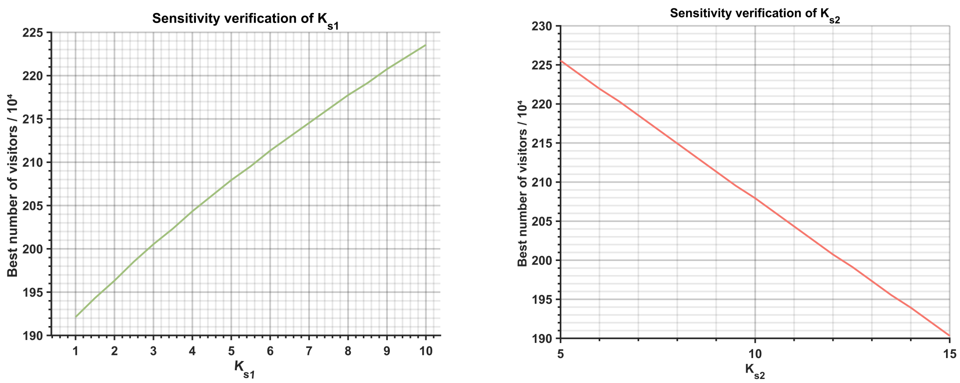


(b) Change E_{max}

Figure 3: Model result

As shown in Figure 3a, when adjusting **the maximum infrastructure capacity ($I_{\mathbf{max}}$)**, the optimal annual number of tourists increases with the rise of $I_{\max}$. At lower values of $I_{\max}$, such as around 20,000, the growth rate of tourist numbers is relatively rapid, indicating that **infrastructure capacity is a critical limiting factor at this stage**. However, as $I_{\max}$ continues to increase, the growth rate of tourist numbers slows down and eventually approaches an upper limit. This is because, **with the improvement in infrastructure capacity, the pressure on infrastructure from additional tourists becomes negligible, reducing the marginal impact of increasing $I_{\mathbf{max}}$**.

As shown in Figure 3b, when adjusting **the maximum environmental capacity ($E_{\mathbf{max}}$)**, the optimal annual number of tourists shows a nearly linear increase. When $E_{\max}$ reaches 100 km^2/year (2.5 times the current glacier melting rate), the optimal annual number of tourists reaches 2.9399 million, which is very close to the upper limit of 3 million. This indicates that **enhancing environmental capacity, such as allowing for higher tolerances of glacier melting, can significantly increase the number of tourists until the environmental capacity is fully utilized**.



(a) Change K_{s2} (b) Change K_{s2}

Figure 4: Model result

As shown in Figure 4a, when adjusting the parameter K_{s1} in the resident satisfaction function S, the optimal annual number of tourists increases as K_{s1} grows. Specifically, as K_{s1} increases from 1 to 10, the optimal annual number of tourists rises from 1.9213 million to 2.2355 million. This suggests that **as residents place greater value on the positive impact of the employment rate, their satisfaction increases, leading them to support higher numbers of tourists**.

As shown in Figure 4b, when adjusting the parameter K_{s2} in the resident satisfaction function S, the optimal annual number of tourists decreases as K_{s2} increases. Specifically, as K_{s2} rises from 5 to 15, the optimal annual number of tourists decreases from 2.2555 million to 1.9033 million. This indicates that **as residents become more sensitive to the negative impacts of excessive tourism, such as overcrowding or disruptions to daily life, they prefer a lower number of tourists**.

3.7.3 The Most Important Factors in the Model

Sensitivity analysis reveals that the tourism revenue weight (w_1) and the environmental pressure weight (w_3) are the most critical factors influencing the optimal annual number of tourists. As w_1 increases, the number of tourists grows linearly, rising rapidly from 700 thousand when $w_1 = 0.05$ to the maximum capacity of 3 million when $w_1 = 0.8$. This indicates that policies prioritizing economic benefits can significantly drive tourist growth.

In contrast, w_3 imposes a clear restrictive effect on the number of tourists. As w_3 increases from 0.05 to 0.95, the number of tourists plummets from 3 million to 93,060. Since natural landscapes are the core attractions of Juneau, this highlights the critical importance of environmental protection in ensuring sustainable tourism growth.

The sensitivity analysis of these two weights in the model shows that economic income and environmental pressure are the most important factors in the model. Sustainable tourism policies must strike a balance between these two factors in order to achieve sustainable tourism.

4 Sustainable Tourism Industry Model for Hawaii

4.1 Establishment of a Comprehensive Multi-Objective Optimization Model

As we all know, Hawaii is also suffering from overtourism. Therefore, we aim to apply our previously developed multi-objective optimization model to the Hawaiian Islands. We mainly focus on **Oahu Island, Maui County, Hawaii Island, and Kauai Island**, with Maui County encompassing Maui Island, Molokai Island, and Lanai Island.

4.1.1 Establishment of Models for different destinations

Firstly, the formula for infrastructure pressure I in Hawaiian Islands differs from that in Juneau. Since the report[3] does not provide rank for ports in Hawaii, we have replaced the port component in the infrastructure assessment with coastal areas, as mentioned in the report. Using the updated weights for infrastructure, we have derived the infrastructure score for Hawaii:

$$\text{Score}_{\text{Hawaii\_infra}} = \sum_i (\text{Weight}_i \times \text{Score}_i) = 1.5998 \tag{13}$$

Subsequently, we construct the infrastructure pressure formulas for the four main tourist destinations—Oahu Island, Maui County, Hawaii Island, and Kauai Island—based on the infrastructure score of Hawaii:

$$I = \frac{P_{\text{local}} + x \cdot \frac{X_{\text{daily\_max}}}{X_{\text{annual}}}}{\text{Score}_{\text{Hawaii\_infra}}} \tag{14}$$

Where X_{annual} is **the annual maximum number of tourists on each of Hawaii's tourist islands**, which is uniformly assumed to be 6,000,000 based on the data, and X_{daily_max} is **the daily maximum number of tourists**, which is assumed to be twice the average daily number of tourists on the islands according to the data.

Next, we need to update our revenue function R. Based on the various tax[7] rates applied to tourist expenditures in the state of Hawaii, we calculate **the total tax rate t=17.962%**. Substituting these parameters into equation (2), we derive new revenue function R in Hawaii.

Also, we need to derive the resident satisfaction S for Hawaii. Based on the annual unemployment rate in Hawaii [8] and the annual number of visitors to the four major tourist islands[9], we use **exponential data fitting method** to establish the relationship between the unemployment rate (%) and the annual number of visitors to the islands. The parameters for each location are as follows: **(1) Oahu:** $a = 19.66$, $b = -3.439 \times 10^{-7}$; **(2) Kauai:** $a = 19$, $b = -1.439 \times 10^{-6}$; **(3) Maui:** $a = 20.52$, $b = -6.743 \times 10^{-7}$; **(4) Hawaii:** $a = 21.17$, $b = -1.162 \times 10^{-6}$. Subsequently, by substituting parameters into formula (16), we obtain the resident satisfaction function for each tourist island.

Regarding the environmental pressure term, we focus on the **coral bleaching** problem in Hawaii. Through the greenhouse effect, visitors' carbon emission translates into a rise in seawater temperature, ultimately triggering widespread coral bleaching and death.

By establishing a four-dimensional dynamic system linking visitor volume, transportation carbon emissions, seawater temperature rise, and coral bleaching rate, we quantify the nonlinear relationship between **visitor volume** and **coral bleaching rate**, reflecting the pressure exerted by Hawaii's visitor volume on marine ecosystems.

Utilizing conclusions from previous environmental pressure analyses in Juneau, the **temperature increase** caused by carbon emissions from tourism is **logarithmically** related to **visitor volume**[4], expressed as:

$$\Delta T = \mu \ln(C_1 x)$$

where ΔT is the temperature increase, and x represents visitor volume.

The rise in seawater temperature directly threatens the survival of coral communities and disrupts the symbiotic relationship between corals and other species, such as zooxanthellae. According to *Heat stress and bleaching in corals: a bioenergetic model*[12], the **temperature increase** ΔT and the **coral bleaching rate** (Environmental pressure) E_{coral} exhibit an **exponential** relationship:

$$E_{\text{coral}} = C_0 e^{\lambda \Delta T}$$

Substituting ΔT, we get:

$$E_{\text{coral}} = C_0 e^{\lambda \mu \ln(C_1 x)} = C_0 (C_1 x)^{\lambda \mu}$$

Let $K_{E0} = C_0 \cdot C_1^{\lambda \mu}$ and $n = \lambda \mu$. Then:

$$E_{\text{coral}} = K_{E0} x^n$$

Using coral bleaching area data[13] from the Pacific Islands Fisheries Science Center (PIFSC) for 2015–2019 and visitor volume data from Hawaii's Annual Visitor Research Report, we fit the coefficients in the equation. A **cubic** function provides the smallest residual error, yielding:

$$K_{E0} = 5.921 \times 10^{-8}$$

Thus, the final equation for **coral bleaching rate (Environmental pressure)** is:

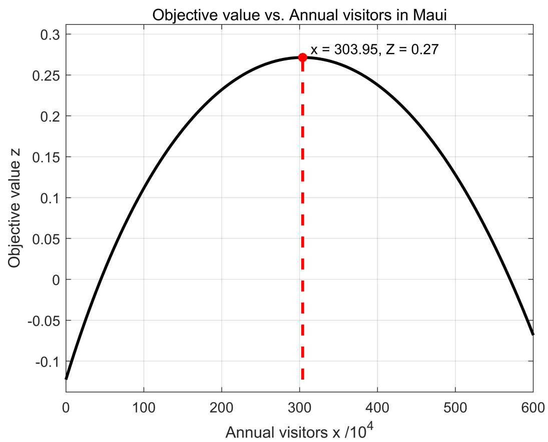
$$E_{\text{coral}} = 5.921 \times 10^{-8} x^3$$

4.1.2 Results and Analysis

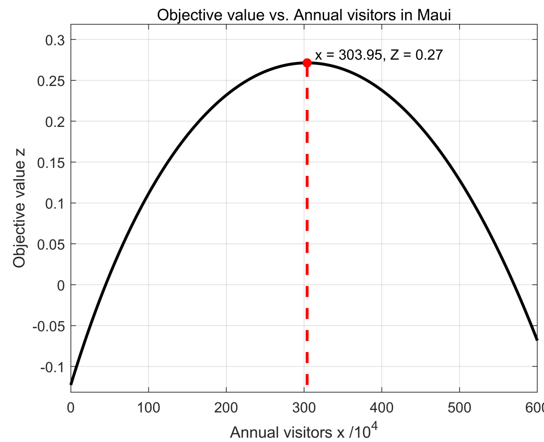
By incorporating the updated infrastructure pressure function I, revenue function R, resident satisfaction S, and environmental pressure E_{coral} into the comprehensive multi-objective optimization model, we calculate **new objective function** $Z(x)$:

$$Z(x) = w_1 \cdot \left(\frac{R(x)}{R_{\max}}\right) - w_2 \cdot \left(\frac{I(x)}{I_{\max}}\right) - w_3 \cdot \left(\frac{E_{coral}(x)}{E_{\max}}\right) - w_4 \cdot (1 - S(x)); \tag{15}$$

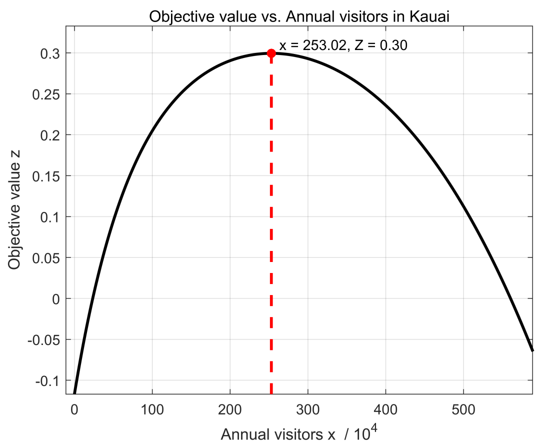
where the weights w_1, w_2, w_3 and w_4 remain consistent with those used in the objective function for Juneau. $R_{\max}$: represents **the maximum tourism revenue for different destinations**; $I_{\max}$: represents **the maximum infrastructure capacity of different destinations**; $E_{\max}$: represents **the acceptable maximum annual coral bleaching rate of Hawaii islands**. This allows us to derive the relationship between **the objective score Z and the annual number of visitors for each of the four tourist destinations**, as illustrated in the following graph:



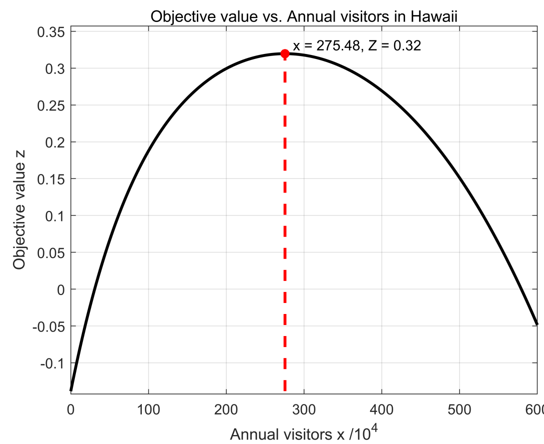
(a) Objective value vs. Annual visitors in Oahu



(b) Objective value vs. Annual visitors in Maui



(c) Objective value vs. Annual visitors in Kauai



(d) Objective value vs. Annual visitors in Hawaii

As shown in the graph, the optimal number of visitors and the maximum objective score for the four tourist destinations are as follows: **(1) Oahu:** $x = 3,299,019$**,** $z = 0.15586$**; (2) Kauai:** $x = 2,530,203$**,** $z = 0.29945$**; (3) Maui:** $x = 3,039,525$**,** $z = 0.27137$**; (4) Hawaii:** $x = 2,754,843$**,** $z = 0.31964$. In 2023, the annual number of visitors to these four destinations[9] was: **Oahu: 5,613,409; Kauai: 1,418,688; Maui: 2,531,196; Hawaii: 1,779,063**.

From this, we can infer that Oahu Island is experiencing **excessive pressure from tourism**, and some of these visitors could be redirected to other destinations. The other islands still **have the capacity to accommodate additional tourists**.

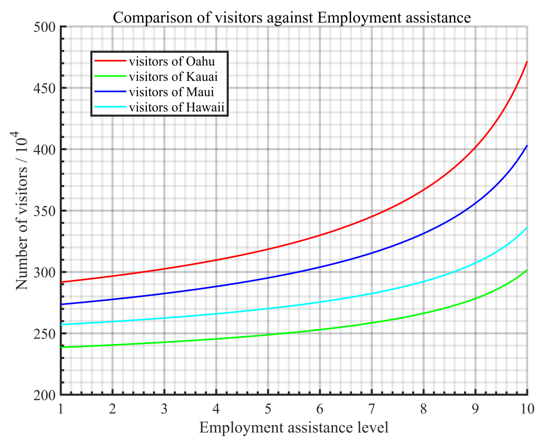
4.2 Impact of Different Measures

We examined the effects of varying **levels of employment assistance, tourist coral reef protection rates, and infrastructure scores across different major tourist destinations**, employing a controlled variable approach for all adjustments.

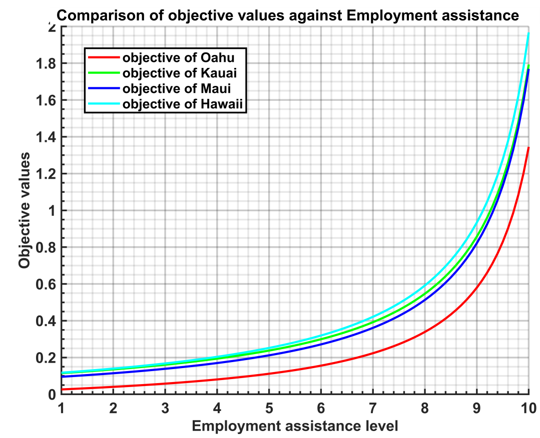
First, we analyzed **the impact of employment assistance**. By providing unemployed residents with job training and a certain level of unemployment subsidies, we divided this assistance into 10 levels. The resident satisfaction S under these conditions is as follows:

$$S = K_{S0} + 5 \cdot K_{S1} \cdot \left(1 - ae^{bx}\right) / (11 - K) + K_{S2} \cdot e^{K_{S3} \cdot x} \tag{16}$$

where K represents **the level of employment assistance**. By default, the employment assistance is set to a medium level, i.e., level = 5. We can observe the relationship between **the maximum objective score, the optimal annual number of visitors, and varying levels of employment assistance for the four major islands**, as illustrated in the following graph:



(a) Annual visitors vs. Employment assistance

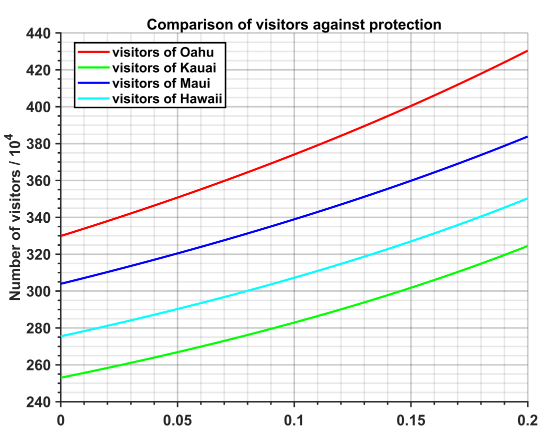


(b) Objective value vs. Employment assistance

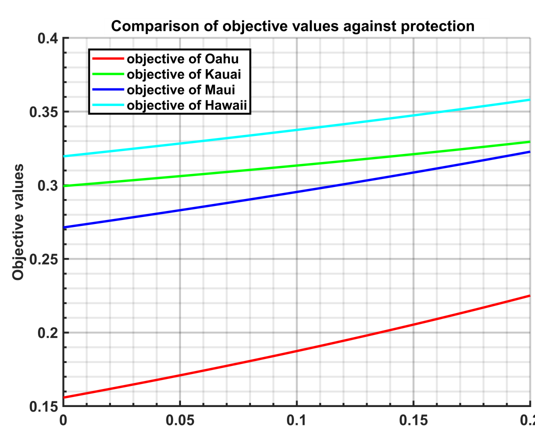
Next, we analyze **the impact of the tourist coral reef protection rate**. We assume that an increase in the protection rate will reduce the extent of coral damage caused by tourists. Therefore, we modify the environmental pressure function E_{coral} for Hawaii as follows:

$$E_{\text{coral}} = K_{E0}((1 - r_{protection}) \cdot x)^n \tag{17}$$

where $r_{protection}$ means **the rate of protection from visitors**. From this, we can derive the relationship between **the maximum objective score, the optimal annual number of visitors, and the coral reef protection rate for each tourist destination**, as illustrated in the following graph:

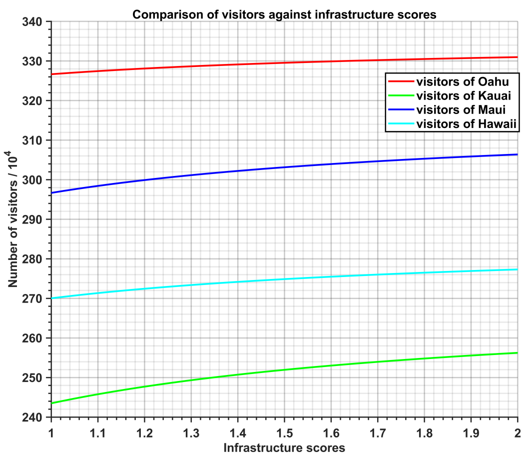


(a) Annual visitors vs. Protection rate

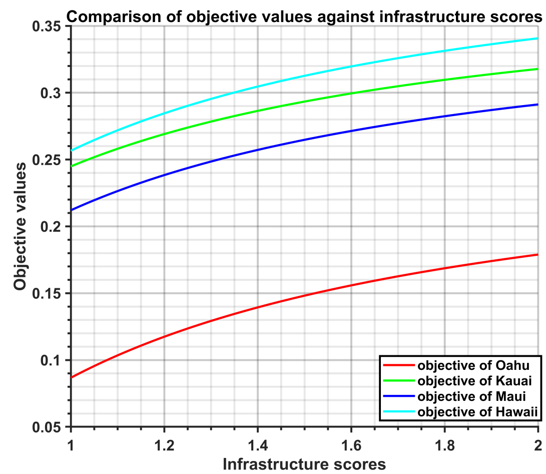


(b) Objective value vs. Protection rate

Finally, we analyze **the impact of infrastructure development on the different islands**. Based on the infrastructure pressure function I for the Hawaiian Islands, we examine the effects of varying the infrastructure score $Score_{Hawaii\_infra}$ from 1.0 to 2.0 on **the maximum objective score and the optimal annual number of visitors** for each tourist destination, while keeping all other parameters constant. The results are as follows:



(a) Annual visitors vs. Infrastructure scores



(b) Objective value vs. Infrastructure scores

Based on the above results, we can draw the following conclusions:

1. **Increasing Employment Assistance to Level 8 or Higher**: (1) The maximum objective scores for all four tourist islands will significantly improve; (2) The optimal annual number of visitors for Oahu Island will **experience a more pronounced increase compared to the other three locations**, reaching a peak of approximately 4,750,000 visitors.

2. **Increasing the Coral Reef Protection Rate**: (1) This will significantly increase the optimal annual number of visitors for all four tourist islands, **particularly for Oahu Island**; (2) The relationship curves between the maximum objective score and the protection rate are **nearly parallel for all islands** except Kauai Island, where the protection rate does not significantly improve the objective score.

3. **Improving Infrastructure Development**: (1) Infrastructure improvements do not significantly affect the optimal annual number of visitors for **Oahu Island and Hawaii Island**; (2) However, they have **a more substantial impact on Maui Island and Kauai Island, especially the latter**; (3) The relationship curves between the maximum objective score and infrastructure score are **similar for all four islands**, though there are notable differences in the objective scores.

Recommendations: (1) To mitigate the negative impacts of overtourism on Oahu Island, local governments should focus on promoting coral reef protection, raising tourists' environmental awareness, and improving employment opportunities for residents. (2) To increase the optimal number of visitors for Kauai Island, enhancing infrastructure development is an essential measure.

4.3 Attractiveness Model

The attractiveness of different tourist attractions to visitors is influenced by various factors, such as infrastructure conditions, policies, and consumption differences across destinations.

For a given total visitor volume , the **ratio of visitor volumes** between destinations can be considered as the **ratio of attractiveness** to those attractions. Specifically, for Hawaii, the attractiveness of its four main islands is represented by the normalized visitor volume to each island:

$$A_i = \frac{x_i}{\sum_{j=1}^{n} x_j} \tag{18}$$

here A_i is the **attractiveness** of the i-th island, and x_i is the visitor volume to the i-th island.

To evaluate the effectiveness of different measures in enhancing the attractiveness of a destination, it is necessary to determine the ratio of visitor volumes between destinations under a given total visitor volume to the tourist destination.

In previous discussions, we established the relationship between the objective function Z_i of each of Hawaii's four islands and the visitor volume x_i to that island.

Note that the sum of the objective functions of all islands, $\sum Z_i$, represents the total objective function for Hawaii, and a higher value is preferable. Thus, under the constraint of a fixed total visitor volume to Hawaii, the **optimal distribution of visitor volumes** x_i is the one that **maximizes the total objective function**. The relative attractiveness of each island can then be obtained by normalizing the visitor volumes x_i.

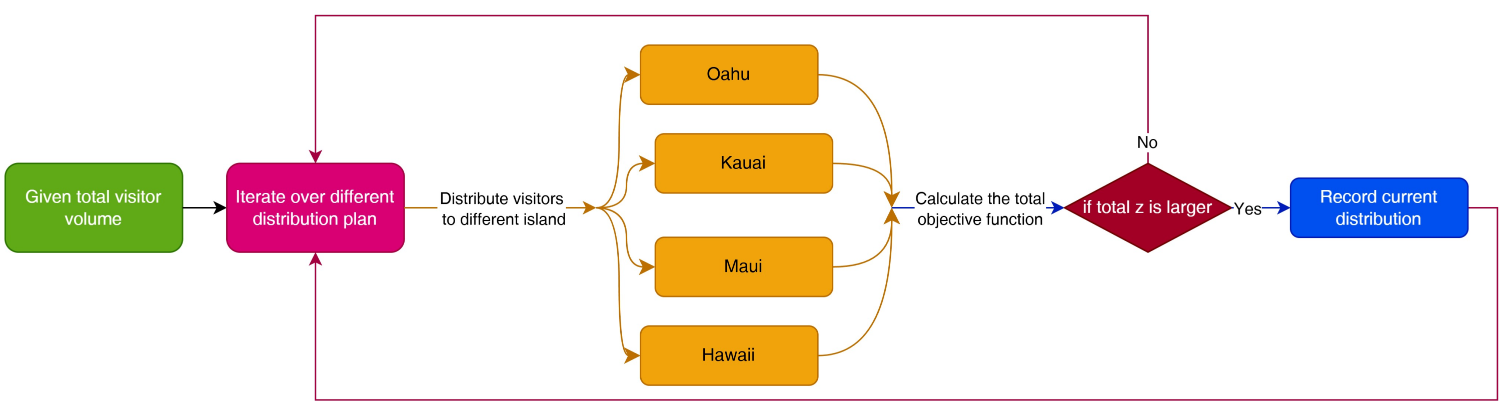


Figure 9: Structure of Attractiveness Model

Based on the model, we summarize three effective measures to promote less-visited destinations

4.3.1 Increase infrastructure capacity in less-visited destinations

For less-visited destinations, increasing infrastructure capacity can accommodate more tourists while reducing the pressure on local infrastructure caused by an influx of visitors, thereby enhancing the attractiveness of the destination. Under the default infrastructure parameters of the current model, when Hawaii's total visitor volume is 10 million, the least attractive destination is Kauai Island, with a visitor volume of 2 million, accounting for **20%** of the total visitor volume. As the infrastructure capacity of Kauai Island is increased to **twice its current capacity**, the ratio of visitor volumes (relative attractiveness) among the four islands changes as shown in the figure:

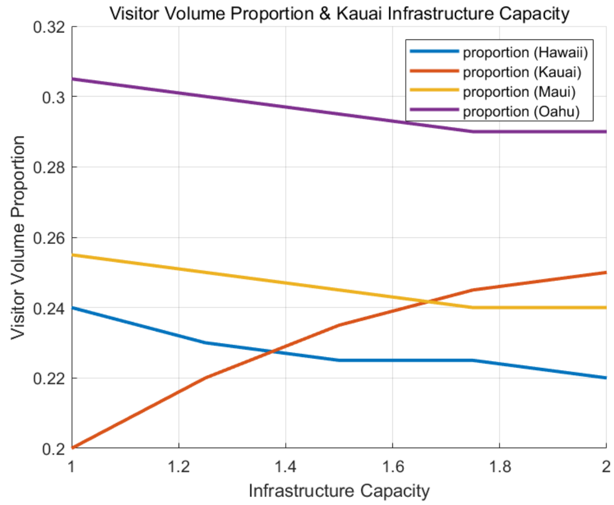


Figure 10: Structure of Attractiveness Model

It can be observed that Kauai Island's proportion of the total visitor volume gradually increases from **20% to 25%**, with the visitor volume rising to **2.5 million**. This effectively promotes tourism to Kauai Island, which previously had fewer visitors.

4.3.2 Reduce tourist taxes and lower per capita consumption in less-visited destinations

Under the same conditions, tourists tend to prefer destinations with lower per capita consumption. Therefore, policies can be implemented to reduce consumption taxes in less-visited destinations while increasing taxes in over-visited destinations, thereby promoting tourism to less-visited areas. Taking Kauai Island as an example, reducing its **tourist tax** from the original **17.962% to 3%** results in the following changes in the ratio of visitor volumes (relative attractiveness) among the four islands, as shown in the figure:

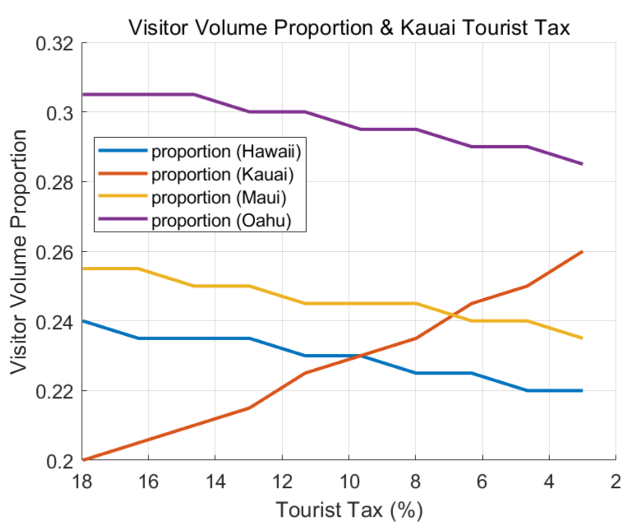


Figure 11: Structure of Attractiveness Model

It can be observed that Kauai Island's proportion of the total visitor volume gradually increases from **20% to 26%**, with the visitor volume rising to **2.6 million**. This effectively promotes tourism to Kauai Island, which previously had fewer visitors.

4.3.3 Set visitor caps for popular destinations to enforce tourist redistribution

In this model, destinations within the same tourist region compete with each other. In Hawaii, the most popular destination is Oahu Island, which, under default parameters, accounts for 30.5% of the total visitor volume. By capping the maximum visitor volume of **Oahu** Island while maintaining the total visitor volume at 10 million, its proportion of the total visitor volume is gradually reduced from **30.5% to 27.5%**. The changes in the ratio of visitor volumes (relative attractiveness) among the four islands are shown in the figure:

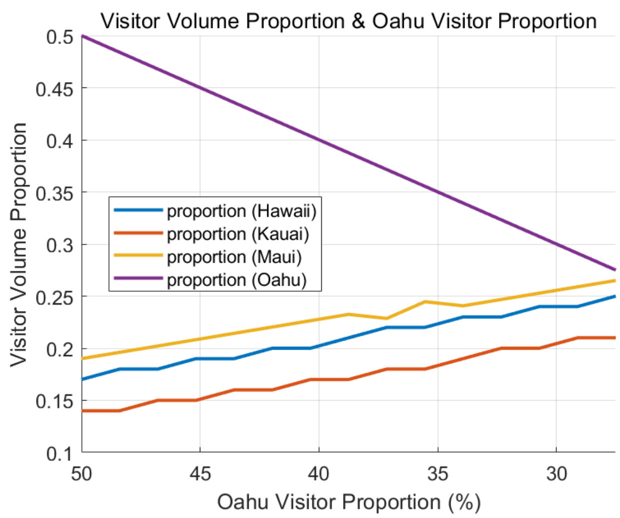


Figure 12: Structure of Attractiveness Model

It can be observed that **Kauai** Island's proportion of the total visitor volume gradually increases from **14% to 21%**, with the visitor volume rising to **2.1 million**. This effectively promotes tourism to Kauai Island, which previously had fewer visitors.

4.4 Sensitivity Analysis

Considering the Multi-Objective Optimization Model for Hawaii established in Section 4.1, which is largely similar to the model used in Section 3 except for differences in certain parameter values, and given that the model in Section 3 has already undergone sensitivity analysis in Section 3.7, no additional sensitivity analysis is needed for Section 4.1.

Here, we conduct a sensitivity analysis for the **Multi-Attribute Resource Allocation Model** proposed in Section 4.2. Compared to the Multi-Objective Optimization Model in Section 4.1, the model in Section 4.2 integrates the models for the four islands. Under a **given total visitor volume** for Hawaii, it calculates the objective function for each island, sums them up, and compares the total objective function to determine the **optimal distribution** of visitor volumes across the islands.

Following the sensitivity analysis conducted in Section 3.7, the Multi-Attribute Resource Allocation Model introduces a new fixed parameter: the **total visitor volume for Hawaii**. Therefore, sensitivity analysis is only required for this parameter. By varying the total visitor volume from **5 million to 15 million**, we observe the changes in the **proportion of visitor volumes (relative attractiveness)** among the islands and compare them with real-world situation.

As the total visitor volume increases, the proportion of visitors among the islands gradually becomes more balanced. Specifically:

- **Oahu** Island, which initially had the highest proportion of visitors, decreases from **45.5% to 28.5%**.
- **Kauai** Island, which initially had the lowest proportion of visitors, increases from **9% to 21.5%**.

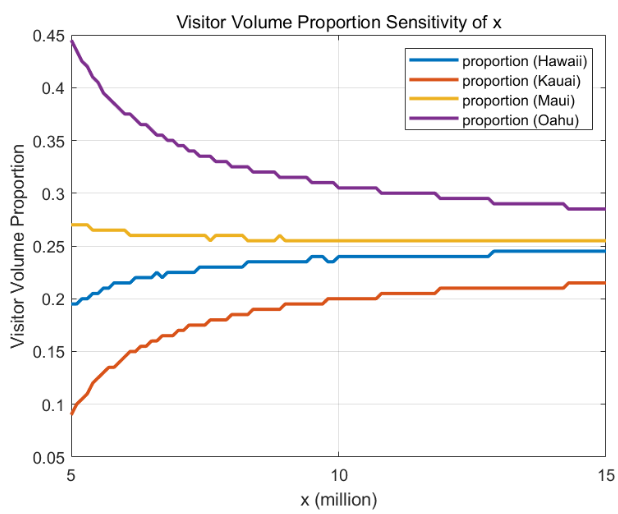


Figure 13: Structure of Attractiveness Model

As the number of tourists increases, the relative attractiveness of Oahu Island, which is the most attractive to tourists, gradually declines due to the immense environmental pressure caused by over-tourism and the collapse of its limited carrying capacity. This phenomenon aligns with real-world observations, as the Hawaiian authorities have been forced to implement additional tourism taxes in some areas due to excessive tourist numbers.

On the other hand, Kauai Island, which is the least attractive to tourists, has redundant carrying capacity, resulting in relatively lower environmental pressure as the number of tourists increases. Its relative attractiveness improves as the total visitor volume grows. This also aligns with the real-world phenomenon of tourist redistribution due to over-tourism in certain areas.

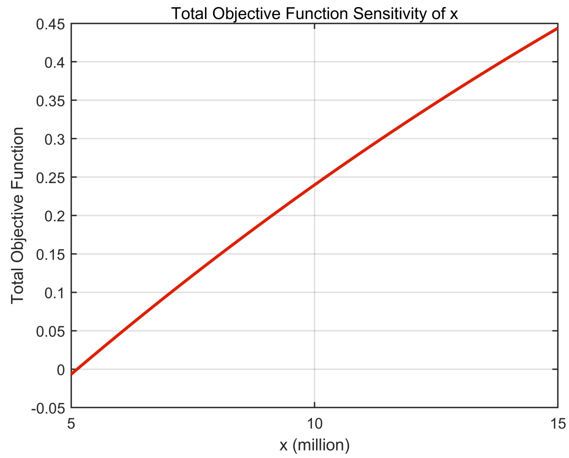


Figure 14: Structure of Attractiveness Model

The contribution of tourism to the islands can be evaluated using the total objective function. As the total visitor volume increases, the total objective function continues to grow, but the growth rate gradually slows. This phenomenon reflects the real-world situation where, as the total number of tourists increases, local revenue generally rises, but the growth rate slows due to environmental pressure and limited local carrying capacity.

5 Strengths and Weaknesses

5.1 Strengths

- The model simultaneously considers **multiple factors including tourism revenue, infrastructure pressure, environmental pressure, and resident satisfaction**. Through comprehensive evaluation with different weights, it enables **holistic simulation of sustainable tourism impacts**.
- By adjusting weight parameters (e.g., w_1, w_2, w_3, w_4), the model's emphasis on different objectives can be modified, allowing **adaptation to various policy requirements and practical scenarios**.
- The Attractiveness model effectively simulates **competitive relationships between tourist attractions, adequately reflects attractiveness disparities**, and demonstrates **how single policies impact all attractions globally**.

5.2 Weaknesses

- The model may overlook seasonal fluctuations in tourist numbers, leading to poorer temporal resolution and reduced correspondence, especially during peak or off-peak seasons.
- The Attractiveness model's assumption that relative attractiveness correlates with visitor volume might oversimplify the situation, causing divergence from reality.

6 Memorandum to the Juneau Tourism Council

To the City of Juneau Tourism Commission:

With the vigorous development of Juneau tourism, the rapid increase in the number of visitors has brought considerable economic benefits, but it has also brought a series of problems. The purpose of this memorandum is to analyze the current and future development trends of Juneau's tourism industry based on our sustainable tourism model, and to provide constructive advice to guide future urban tourism policies.

1. Current Situation and Challenges

In 2023, the city of Juneau welcomed 1.67 million cruise passengers and 350,000 air visitors, generating more than $400 million in revenue. However, too many visitors have brought about a series of problems. The Juneau Icefield, represented by Mendenhall Glacier, is shrinking by more than 35 square kilometers per year due to excess carbon emissions. At the same time, the influx of visitors has led to a sharp increase in pressure on local infrastructure, water supplies are tight, and waste disposal is difficult. Although the development of tourism has brought many job opportunities to local residents, it has also produced rising living costs and problems such as congestion and noise, which has triggered dissatisfaction among some residents.

2. Model Prediction Results

Through the comprehensive multi-objective optimization model built by us, the simulation results are obtained when no control measures are taken: the number of visitors continues to grow uncontrolled, the number of visitors may surge to 3 million per year, and the daily peak number of visitors can reach 34,000, making the infrastructure system on the verge of collapse. The huge amount of carbon emissions brought by visitors may cause the Juneau Icefield to retreat at a rate of 90 square kilometers per year, causing serious damage to the ecosystem, the city of Juneau losing its natural landscape of glaciers, and the satisfaction of residents may drop below 50%. It has caused serious impact on the local natural ecological environment and social stability.

3. Optimize Policy and Effect Analysis

(1) Limit the annual total number of visitors and the daily number of visitors in peak season, control the number of visitors within the affordable range of infrastructure and environment, while maintaining a relatively stable tourism income, help to reduce the pressure on local infrastructure, also help to reduce the carbon emissions brought by visitors, slow down the retreat of glaciers, protect the natural landscape, At the same time, it can avoid the impact of too many visitors on local communities. (2) Levy hotel taxes and tourist taxes on visitors, and use these additional revenues to support environmental protection, improve infrastructure and develop community projects, slow the rate of glacier retreat, increase the capacity of infrastructure, and improve the happiness of residents. (3) Dig deep into the cultural connotation of Juneau City and develop diversified tourism products. For example, the launch of indigenous cultural experience tours, diversified tourism products can extend the stay of visitors, increase the diversity of visitors' consumption, and improve the economic benefits of tourism.

To sum up, Juneau's tourism industry is at a critical development stage. By adjusting the number of visitors, optimizing tax policies, and developing diversified tourism products, sustainable development can be achieved. This approach generates significant tourism revenue while maintaining the stability of the social and natural environment.

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