

CONSTRUCTION OF JUNEAU'S TOURISM SOCIAL COST-ECONOMIC BENEFIT MODEL AND KEY FACTOR ANALYSIS BASED ON AHP AND MULTIVARIABLE ADJUSTMENT

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Abstract: In 2023, Juneau, Alaska, received a record 1.6 million cruise visitors, bringing significant revenue but severe overcrowding. To address this, this study develops a sustainable tourism model prioritizing economic benefit maximization. It uses linear fitting/trigonometric functions for visitor numbers, logarithmic/linear functions for tourism revenue, differential equations for environmental pressure, and the Analytic Hierarchy Process (AHP) for a constrained social cost model. Analysis shows Juneau's total economic benefit peaks at ~1,026,453 visitors, with an income-expenditure plan and feedback mechanism proposed. A multivariable adjustment approach further quantifies impacts of variables (e.g., visitor spending, tax rates) and identifies key factors (e.g., visitor numbers, glacier melting rate) to support tourism decision-making.

Keywords: Sustainable tourism model; Analytic Hierarchy Process (AHP); Economic benefit maximization; Juneau; Multivariable adjustment

1 INTRODUCTION

In the process of tourism development, issues related to overtourism have become increasingly prominent. In 2023, Juneau, Alaska, USA, welcomed 1.6 million cruise passengers, generating \$375 million in tourism revenue, yet it also confronted significant imbalances such as the retreat of the Mendenhall Glacier and escalating pressure on infrastructure [1,2]. Over the past five years, relevant research has made considerable progress both domestically and internationally: Internationally, Kim et al. analyzed the influencing factors of overtourism in Jeju Island using structural equation modeling [3], Bergantino et al. constructed a vulnerability assessment framework for EU tourist destinations via fuzzy comprehensive evaluation [4], Gössling et al. quantified tourism carbon footprints through life cycle assessment (LCA) [5], and another study proposed a multi-objective model integrating system dynamics to address overtourism in Juneau [1]. However, these studies mostly focus on single regions or static evaluations, lacking dynamic quantitative models tailored to cruise tourism scenarios. Additionally, the management framework proposed by the World Tourism Organization only provides macro guidance without offering technical support [6]. Domestically, Yang et al. emphasized the necessity of interdisciplinary quantitative analysis through bibliometrics [7], Feng et al. quantified the characteristics of carbon emissions in scenic areas using meta-analysis [2], Chen et al. established an early warning index system for overtourism in cruise tourism destinations based on the entropy weight method [8], Li et al. measured cruise tourism carbon emissions via the emission factor method [9], and other studies explored the coupling coordination relationship between green finance and high-quality tourism development [10]. Nevertheless, gaps remain in multi-dimensional integrated modeling and variable optimization specifically for cruise tourism scenarios. To address these limitations, this study takes Juneau as the research object, integrates linear fitting, differential equations, and the Analytic Hierarchy Process to construct a tourism revenue-environment-social cost model, innovatively incorporating the irreversible impact of glacial melt and a benefit feedback mechanism, and quantifies the impacts of key factors through multivariable adjustment [1,2]. Subsequent Section 2 elaborates on model construction and solution analysis, while Section 3 presents research conclusions and optimization suggestions, providing decision support for similar destinations.

2 SUSTAINABLE TOURISM INDUSTRY MODEL FOR JUNEAU

2.1 Number of Cruise Passengers in Juneau from 2014 to 2023

The data on the number of cruise passengers in Juneau from 2014 to 2023 is obtained from the ECONOMIC IMPACT OF JUNEAU'S CRUISE INDUSTRY 2023 [1], as shown in Figure 1.

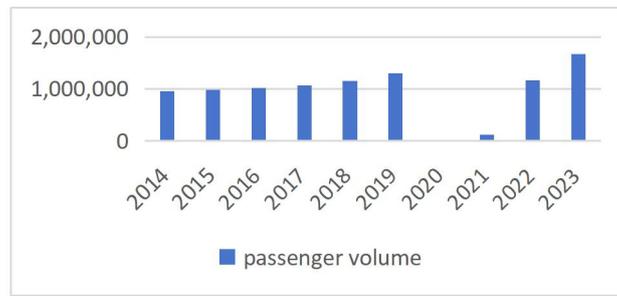


Figure 1 Juneau Cruise Passenger Volume, 2014-2023

Due to the impact of the pandemic, the number of tourists in 2020 and 2021 significantly decreased and is not considered to be of reference value. Therefore, the data for 2020 and 2021 will be excluded from this study.

2.2 Optimization Target Model

In this paper, to achieve a sustainable tourism industry model, a goal function is established with the objective of economic maximization,

$$\max Z = R - C_{env} - C_{soci} \quad (1)$$

In this function, R represents the total revenue of the tourism industry, C_{env} represents the environmental pressure cost, and C_{soci} represents the social pressure cost.

2.2.1 Tourist quantity model

The increase in the number of tourists not only affects the city's revenue but also brings about issues related to overcrowding, such as increased pressure on local infrastructure and a heavier environmental burden.

In this paper, Let $q(t)$ represent the number of tourists visiting Juneau each year. Based on the processed cruise passenger data from 2014 to 2023, a linear fit is performed to obtain the tourist quantity model,

$$q(t) = 82337.77t - 164945132.98 \quad (2)$$

Let $N(t)$ represent the number of tourists visiting Juneau each day. Considering the existence of off-peak and peak seasons, the following daily tourist model is established,

$$N(t) = 8000 \sin \frac{2\pi t}{365} + 11000 \quad (3)$$

2.2.2 Tourism revenue model

According to the ECONOMIC IMPACT OF JUNEAU'S CRUISE INDUSTRY 2023, this paper divides the tourism industry revenue into labor income, business revenue, and taxes. All three are closely related to the number of tourists: labor income exhibits diminishing marginal returns as the number of tourists increases, business revenue changes linearly with the number of tourists, and taxes take into account labor, business revenue, and other sources (such as docking fees).

$$R_l = R_s \cdot \ln(e + N) \quad (4)$$

$$R_b = N \cdot C_{avg} \quad (5)$$

$$R_{tax} = \alpha_l \cdot R_l + \alpha_b \cdot R_b + R_o \quad (6)$$

where R_l represents labor income, R_b represents business revenue, R_{tax} represents taxes, R_s represents the initial per capita labor income of local residents, N represents the number of tourists, C_{avg} represents the per capita consumption level of tourists, α_l represents the labor tax rate, α_b represents the business tax rate, and R_o represents other taxes.

Based on the above, the total revenue of the tourism industry is,

$$R = R_l + R_b + R_{tax} \quad (7)$$

2.2.3 Environmental pressure model

Overtourism will significantly impact the natural environment of Juneau. This article mainly considers the impact of tourists on glaciers to describe environmental pressure, with the glacier melt rate primarily determined by regional temperatures.

The glacier melt rate reflected by temperature changes is

$$\frac{dS}{dt} = -k_1 S T \quad (8)$$

where k_1 represents the glacier melt coefficient, S represents the glacier area, and T represents the temperature.

Temperature changes with the number of tourists and greenhouse gas concentrations are represented by

$$\frac{dT}{dt} = k_2 c q \quad (9)$$

$$T = T_0 + k_2 c q \quad (10)$$

where k_2 represents the correlation coefficient between temperature and greenhouse gas concentration, c represents the per capita annual greenhouse gas emissions concentration in the region, and T_0 represents the initial temperature of the region.

Glacier melt rate are represented by

$$\frac{dS}{dt} = -k_1 S (T_0 + k_2 c q) + \gamma \quad (11)$$

where γ represents the background melt rate (the part not affected by temperature).

As the most famous attraction in Juneau, the melting of Mendenhall Glacier will lead to a decline in its appeal to tourists, thereby damaging the future potential of the tourism industry.

$$R_{loss}(t) = R \cdot \left(1 - \left(1 - \alpha_{GR} \cdot \frac{dS}{dt}\right)^t\right) \tag{12}$$

where $R_{loss}(t)$ represents the loss of tourism resources due to glacier melt in a future year, R represents the current annual tourism revenue, and α_{GR} is the sensitivity coefficient of the decline in tourist attraction due to glacier melt.

Based on the above, the future environmental total cost can be expressed as,

$$C_{env} = \sum_{t=0}^{\infty} \frac{1}{(1+r)^t} \cdot R_{loss}(t) \tag{13}$$

where r is the discount rate.

2.2.4 Social cost model

Social costs primarily reflect the negative impacts of overtourism on the well-being of local residents and urban operations, requiring scientific quantification of the comprehensive effects of multi-dimensional costs. Combining the actual situation of Juneau's tourism development and referring to relevant studies on tourist well-being and residents' subjective well-being [11,12], six core social cost indicators were selected: garbage disposal cost, wastewater treatment cost, traffic congestion cost, resident income impact cost, medical expenditure cost, and noise pollution cost. These indicators cover three dimensions: environmental pressure, people's livelihood impacts, and urban operation and maintenance. The selection of indicators is consistent with the research conclusions that "environmental quality, income level, and health status are core factors affecting the well-being of tourism destination stakeholders (tourists and residents)" [11,12], ensuring strong scientificity and pertinence.

To determine the relative importance of the six indicators, the classic 1-9 scale method (Saaty scale) for AHP was adopted: 1 indicates two indicators are equally important; 3 indicates one indicator is slightly more important than the other; 5 indicates significantly more important; 7 indicates strongly more important; 9 indicates extremely more important; and 2, 4, 6, 8 are intermediate values. The reciprocal is used for inverse comparisons.

Building on the aforementioned indicator system and the 1-9 scale method, the judgment matrix A (reflecting the pairwise relative importance of the indicators) was constructed by aligning with the empirically validated impact priorities of income, environment, and health on stakeholders' well-being as documented in relevant studies on the social costs of international tourism destinations [11,12]. This alignment ensured the matrix's consistency with established academic conclusions, and the final judgment matrix A is presented as follows:

$$A = \begin{pmatrix} 1 & 2 & 3 & \frac{1}{2} & 5 & 4 \\ \frac{1}{2} & 1 & 2 & \frac{1}{7} & 3 & 2 \\ \frac{1}{3} & \frac{1}{2} & 1 & \frac{1}{9} & 2 & 1 \\ 2 & 7 & 9 & 1 & 10 & 6 \\ \frac{1}{5} & \frac{1}{3} & \frac{1}{2} & \frac{1}{10} & 1 & \frac{1}{3} \\ \frac{1}{4} & \frac{1}{2} & 1 & \frac{1}{6} & 3 & 1 \end{pmatrix} \tag{14}$$

Normalization processing,

$$A_{norm}(i,j) = \frac{A(i,j)}{\sum_{i=1}^6 A(i,j)} \tag{15}$$

The weights of each indicator are obtained after consistency testing.

The social cost is

$$C_{soci} = \sum_{i=1}^6 w_i c_i(N) \tag{16}$$

The garbage disposal cost is

$$C_1(N) = k_1 \left[\frac{M_1 - (N + N_r) + b_1}{M_1 - N_r + b_1} \right]^{m_1} \tag{17}$$

Here, $M_1 + b_1$ represents the maximum waste capacity of the area, and N_r represents the local population. This formula reflects that when the sum of the local residents and tourists approaches or exceeds $M_1 + b_1$, the garbage disposal cost will increase significantly.

The wastewater treatment cost is

$$C_2(N) = k_2 \left[\frac{M_2 - (N + N_r) + b_2}{M_2 - N_r + b_2} \right]^{m_2} \tag{18}$$

Here, $M_2 + b_2$ represents the maximum wastewater treatment capacity of the area. This formula reflects that when the sum of the local residents and tourists approaches or exceeds $M_2 + b_2$, the wastewater treatment cost will increase significantly.

The traffic cost is

$$C_3(N) = \begin{cases} C_{base}, & N + N_r \leq M_3 \\ C_{base} \cdot e^{k_3(N + N_r - M_3)}, & \& N + N_r > M_3 \end{cases} \tag{19}$$

Here, C_{base} represents the base transportation cost when the healthy tolerance limit M_3 is not reached. When it reaches $N + N_r > M_3$, the transportation cost increases exponentially.

The cost of residents' income, medical costs, and noise costs have a logarithmic relationship with the sum of the number of tourists and local residents,

$$C_i(N)=k_i \cdot \ln(N+N_r+1), i=4,5,6 \tag{20}$$

2.3 Constraints

Constraint conditions play a crucial role in the sustainable development of tourism, as they ensure that tourism activities are conducted within the environmental carrying capacity and the socially and economically acceptable limits. This paper sets three key constraints: the number of tourists, the economy, and social factors. Achieving a balance and coordination among these three elements is vital for the long-term sustainable development of the tourism industry.

2.3.1 Constraints on the number of tourists

Here, $N(t)$ is the core variable in scenic area management. By limiting the number of tourists, controlling social costs, environmental pressures, and economic impacts becomes a necessary condition for maintaining the sustainable development of tourism. The expression for the tourist number constraint is as follows,

$$\begin{cases} 0 \leq N(t) \leq N_{max} \\ N_{max} = \min\{C_{ecological}, C_{physical}\} \end{cases} \tag{21}$$

Here, N_{max} represents the maximum daily visitor capacity of the scenic area, $C_{ecological}$ denotes the ecological carrying capacity, and $C_{physical}$ refers to the physical carrying capacity (such as facility capacity, scenic area size, etc.). According to relevant literature, this paper sets the upper limit of N_{max} at 19,000 visitors.

2.3.2 Economic constraints

Economic constraints are designed to ensure the sustainable development of the tourism industry, preventing long-term losses or over exploitation of resources due to insufficient revenue. The economic constraint is expressed as:

$$R \geq C_{soci} + C_{env} \tag{22}$$

Here, R represents the total tourism revenue, C_{soci} represents the social costs, and C_{env} represents the comprehensive environmental costs.

2.3.3 Social carrying capacity constraint

The social carrying capacity constraint is instrumental in preserving the harmony and sustainable development of local communities, ensuring that the tourism industry respects and protects local culture and social structures while promoting economic growth. This paper establishes a social carrying capacity constraint to limit the ratio of tourist numbers to the local resident population:

$$\frac{N(t)}{N_r} \leq \gamma_{max} \tag{23}$$

N_r represents the local resident population, and γ_{max} represents the maximum tourist-to-resident ratio. This constraint ensures that tourism activities do not unduly disrupt the daily lives of local residents while promoting harmonious development between the tourism industry and the local community.

$$C_i(N)=k_i \cdot \ln(N+N_r+1), i=4,5,6 \tag{24}$$

2.4 Solution and Analysis of the Sustainable Tourism Industry Model

2.4.1 Tourism revenue

Based on the literature provided in the problem statement, the annual tourist volume is limited to 200,000 visitors. By adjusting the labor tax rate α_l and the business tax rate α_b , the changes in revenue with varying tourist volumes can be observed, as shown in Figure 2.

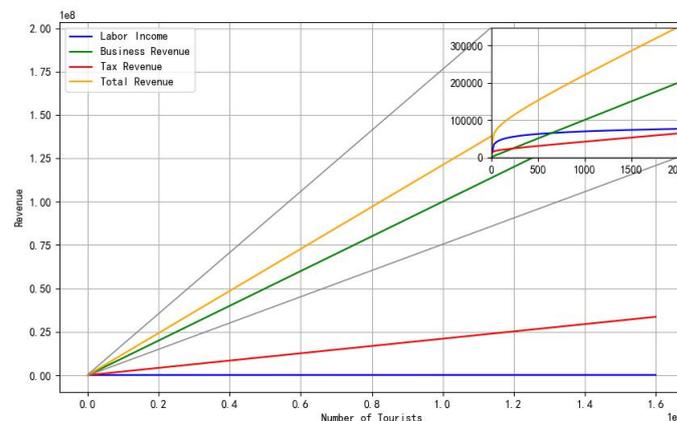


Figure 2 Tourism Revenue Components vs. Number of Tourists

From the Figure 2, it is evident that labor income, business revenue, and taxes all increase with the growing number of tourists, exhibiting a direct proportional relationship.

2.4.2 Environmental pressure

The average carbon emissions per capita in natural scenic areas are approximately 66.13 kg[2]. Utilizing formula (11), the rate of glacier melting can be determined, as shown in Figure 3.

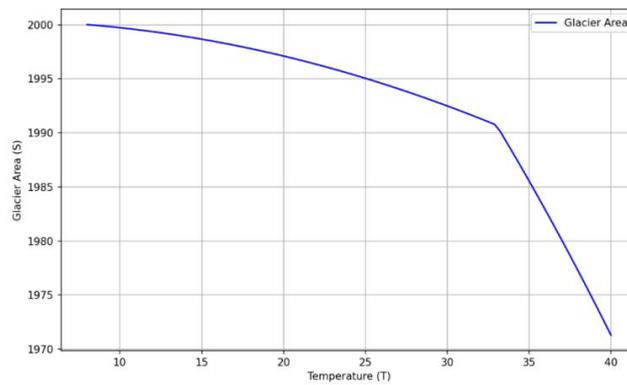


Figure 3 Glacier Area vs Temperature

According to Figure 3, as the temperature increases, the glacier area is continuously melting away, and it will experience a sharp decline once the temperature reaches approximately 32°C [13]. The melting of the Mendenhall Glacier leads to a decrease in its appeal to tourists, thereby causing damage to the tourism potential.

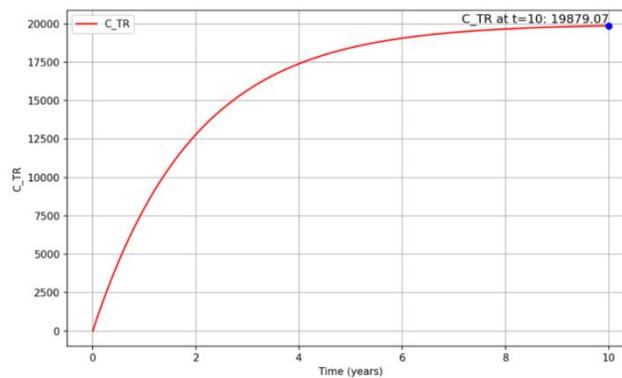


Figure 4 Trend Analysis of Tourism Industry Damage Over Time

According to Figure 4, as temperatures rise over time, the area of glaciers continues to melt, causing increasing damage to Juneau City's tourism industry [14]. Calculate the comprehensive environmental cost:

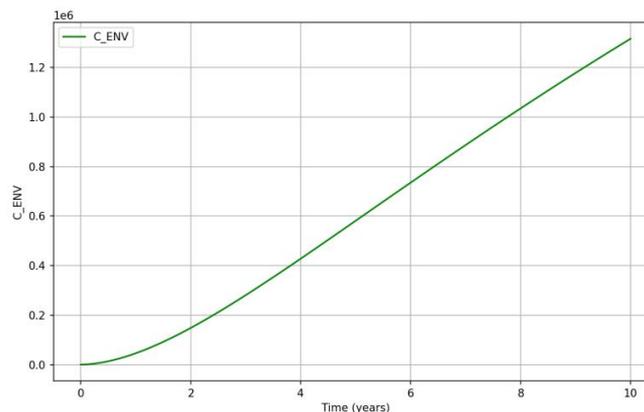


Figure 5 C_{ENV} Over Time

According to Figure 5, as the number of tourists increases over time, the comprehensive environmental cost also continues to rise.

2.4.3 Social costs

This paper calculates social costs using the Analytic Hierarchy Process (AHP) method, and through Python, it obtains the relationships between waste, water pollution, traffic congestion, resident income, healthcare, noise costs, and total costs as they change with the number of tourists, as shown in the following figure 6.

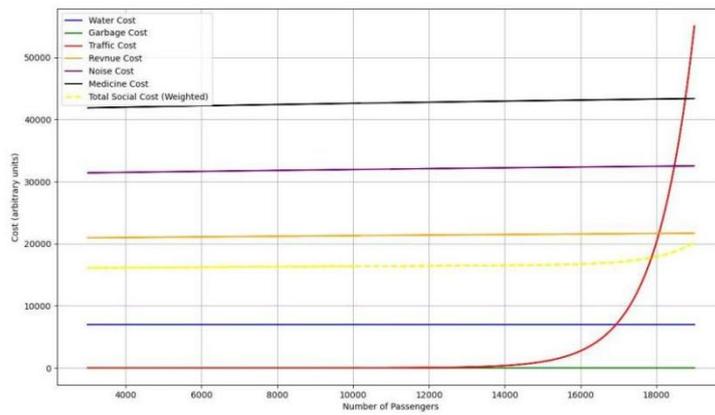


Figure 6 Social Costs vs. Number of Passengers (Weighted by AHP)

According to Figure 6, all social costs exhibit a slight upward trend with the increase in the number of tourists, and transportation costs rise sharply after the daily tourist volume reaches approximately 16,000. Based on the daily tourist model, the relationships between waste, water pollution, traffic congestion, resident income, healthcare, noise costs, and total costs and the number of days within a year are depicted in Figure 7.

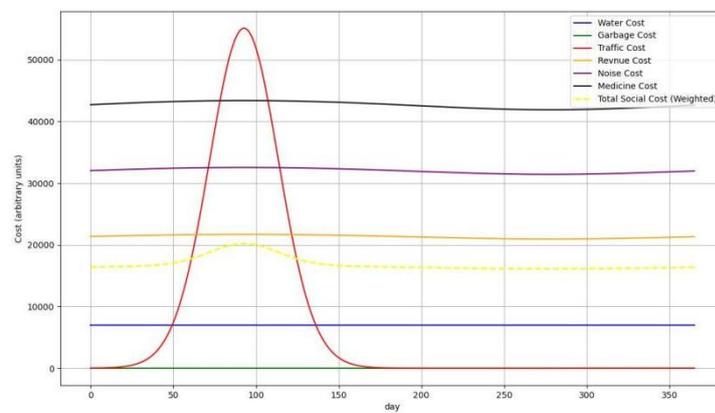


Figure 7 Social Costs vs. Day

2.4.4 Solution of the objective function

Based on the analysis, considering both tourism revenue and environmental and social costs, the change in the total economic benefits of Juneau City with the increase in tourist numbers is depicted in Figure 8.

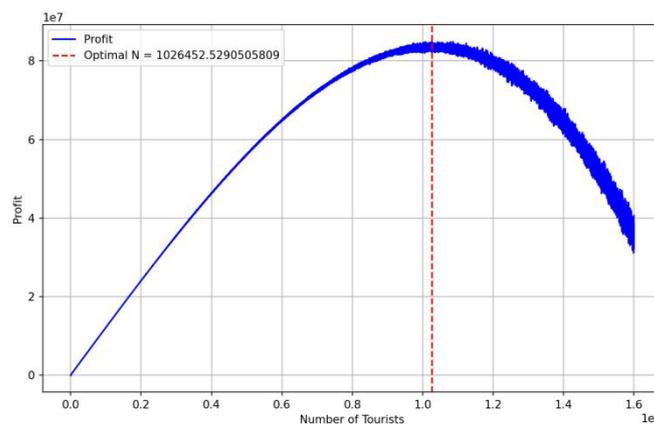


Figure 8 Tourism Profit Maximization

According to Figure 8, as the number of tourists increases, the total economic benefit of Juneau City initially grows and then decreases. The maximum total economic benefit occurs when the annual tourist volume is approximately 1,026,453 visitors, reaching \$84,983,510.43.

2.5 Expenditure Plan and Feedback Mechanism

2.5.1 Infrastructure construction expenditure

Allocate a portion of the additional income to the improvement of transportation infrastructure, such as widening roads and adding public transit routes, which can directly reduce transportation costs and enhance the convenience of tourists' travel, attracting more visitors (as shown in the diagram). This, in turn, promotes tourism consumption, increases municipal tax revenue, and ultimately feeds back into additional income, forming a virtuous cycle. Additionally, investment in sewage treatment and waste disposal facilities can reduce the costs of sewage treatment and waste management, improve the tourism environment, and enhance the attractiveness of the destination.

2.5.2 Investment in tourism service improvement

Utilizing additional income to train tourism professionals enhances service quality and increases residents' income. High-quality services can attract more tourists, boost tourism consumption, and increase municipal tax revenue, which in turn feeds back into additional income [15]. Moreover, investing in the construction of tourism supporting facilities such as rest areas and viewing platforms also helps to attract more visitors and promote tourism consumption.

2.5.3 Ecological and cultural preservation expenditure

The surplus revenue is allocated to ecological conservation initiatives, such as reducing noise pollution and thereby lowering noise-related costs, to foster a more habitable and visitor-friendly environment that attracts additional tourists. In the realm of cultural preservation, efforts are made to explore, preserve, and showcase local distinctive cultures, enriching the content of tourism products and drawing more visitors. This enhances tourism spending, increases municipal tax revenue, and feeds back into additional income, supporting the sustainable development of tourism.

2.5.4 Feedback mechanism

The feedback mechanism plays a significant role in the development of sustainable tourism. It not only establishes a capital cycle that supports the continuous operation of the tourism industry but also promptly reflects market demands, guiding the development of marketable tourism projects. Additionally, it promotes industrial integration and enhances the ecological stability of the industry, comprehensively improving the sustainable development capabilities of the tourism sector.

This paper constructs an optimization model aimed at maximizing economic benefits, yielding an additional profit Z_0 , which is then invested in covering social costs. By increasing investment in social costs, this mechanism fosters economic growth feedback. The feedback mechanism is illustrated in Figure 9.

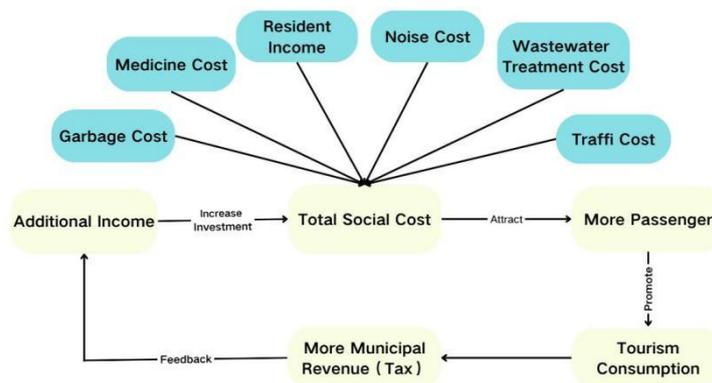


Figure 9 Feedback mechanism flowchart

3 CONCLUSIONS

Overall, this paper centers on the overtourism problem in Juneau, Alaska's tourism sector in the USA, via building a tourism revenue - environment - social cost model. Relying on the cruise passenger data from 2014 to 2023 (except for 2020 and 2021 data) in the 2023 Economic Impact of Juneau's Cruise Industry, an optimization objective model is established. This model consists of an objective function and sub - models regarding tourist volume, tourism revenue, environmental pressure, and social cost. Restrictions on tourist volume, economy, and social carrying capacity are also determined. After solving and analyzing, when the yearly tourist volume is capped at 200,000, different revenues grow proportionally with the increase in tourist numbers, and environmental and social costs rise correspondingly. The total economic benefit first goes up and then declines, peaking at \$84,983,510.43 when the annual tourist volume is around 1,026,453. According to these results, expenditure schemes for infrastructure construction, tourism service enhancement, and ecological and cultural preservation are put forward, and the crucial role of a feedback mechanism in sustainable tourism development is stressed.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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