

# Research on the sustainable tourism development of Juno City based on Stackelberg game and GA-PSO-SA algorithm

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**Abstract.** Balancing tourism's economic benefits with ecological conservation poses a critical challenge for sustainable tourism management. This study proposes a multi-objective optimization model that integrates hidden cost quantification and dynamic policy tools with intelligent algorithms to generate scientific resource allocation schemes for tourism destinations. A case study in Juneau, USA, addresses economic benefits, environmental costs (e.g., carbon emissions), and social satisfaction under constraints such as carrying capacity and infrastructure investment. By combining Stackelberg game equilibrium and hybrid algorithm optimization (GA-PSO-SA), results demonstrate that the optimal carrying capacity reaches 2,165 people/day (game equilibrium), whereas the hybrid algorithm achieves a higher capacity of 2,583 people/day. Implementing stepped taxes and dynamic pricing reduces carbon emissions by 14% and increases resident satisfaction by 23%. Sensitivity analysis identifies environmental carrying capacity as the most influential parameter. This model provides actionable solutions for over-tourism management, demonstrating both theoretical and practical value for sustainable tourism governance.

**Keywords:** Multi-objective optimization, Hidden costs, Sustainability, Stackelberg game, Hybrid algorithm.

## 1. Introduction

Tourism, as a key driver of global economic growth, faces substantial challenges in achieving sustainable development. According to the World Tourism Organisation, international tourist arrivals reached 1.5 billion in 2019, yet 78% of heritage sites are at risk of ecological degradation [1]. Early studies predominantly relied on cost-benefit analysis (CBA) to evaluate tourism's economic impacts, yet overlooked the nonlinear feedback mechanisms of ecosystems [2]. Subsequent research introduced life-cycle assessment (LCA) to measure environmental pressures but failed to integrate social dimensions [3]. Recent advancements in multi-objective optimisation frameworks (e.g., Marzouki et al. [4]) address dual objectives but lack dynamic policy adaptability. While game-theoretic approaches (e.g., Zhang et al. [5]) enhance policy design, they neglect hidden cost accumulation. In contrast, hybrid meta-heuristic algorithms exhibit notable advantages by incorporating multiple search mechanisms [6], yet their synergy with dynamic policy tools remains underexplored. This study aims to (1) quantify dynamic externalities of tourism activities and (2) design a hybrid algorithm integrating GA-PSO-SA and Stackelberg game to optimise multi-dimensional objectives under dynamic constraints.

## 2. Materials and methods

### 2.1. Data acquisition and pre-processing

The data sources for this study are extensive and relevant, and include a variety of sources such as Juneau City Council reports, glacier monitoring data, and resident satisfaction surveys. Visitor data: the number of visitors arriving in the City of Juneau via different modes of transport, including cruise ships, air and road, was collected in detail for the period from 2019 to 2023. The mean daily number of visitors from 2019 to 2023 was recorded as 16,700, sourced from Juneau City Council's annual tourism reports [7-8]. These data provide a solid basis for gaining insight into visitor travel patterns, changes in traffic, and tourism market activity.

In the context of environmental data, the area change of the Mendenhall Glacier from 1770 to 2019 was obtained, which is of great significance for analyzing the glacier's evolutionary trend in the context of long-term tourism development. In addition, the carbon emission coefficients of the different modes of transport were analyzed. of transport (cruise ships, airways, etc.) were determined with high precision, with the carbon emission coefficients of cruise ships being 1.5 times higher than those of airways, providing a quantitative basis for accurately evaluating the environmental pressure caused by tourism [9]. Social data: A comprehensive resident satisfaction survey revealed that 46% of residents held an ambivalent attitude towards tourism, indicating that while tourism development has brought economic benefits to residents, it has also triggered some negative effects [10]. Furthermore, 74% of residents expressed support for imposing a daily cruise limit of five ships, reflecting their expectations and demands for controlling the scale of tourism activities.

Following the acquisition of the raw data, a meticulous procedure of data pre-processing was implemented to ensure the quality and reliability of the model inputs. Initially, the normalization method was employed to transform the data, which varied in scale, into a uniform dimensionless form, thereby ensuring the comparability of the data within the same numerical range. Subsequently, the outliers present within the dataset were identified and removed through the utilization of an outlier detection and removal algorithm, with the objective of preventing the biased impact of these abnormal data on the model results. The preprocessed data can more accurately reflect the real characteristics of the tourism-related information of Juneau City, providing high-quality data support for the construction and solution of the subsequent model.

## 2.2. Methodology

A quantitative analysis was conducted on several abstract influencing factors, including resident satisfaction, infrastructure congestion, and ecological irreversible damage, amongst others. These variables were standardized with the objective of simplifying the calculation process and reducing errors. The analysis of the correlation coefficients revealed that the factors exhibiting the highest correlation were glacier ablation rate and resident satisfaction. Furthermore, implicit drivers of water resources and waste disposal costs were identified, and these implicit drivers were subsequently employed as constraints. Concurrently, the economic, social and environmental models were constructed to reflect the optimal tourism development index from different perspectives(see Figure1).

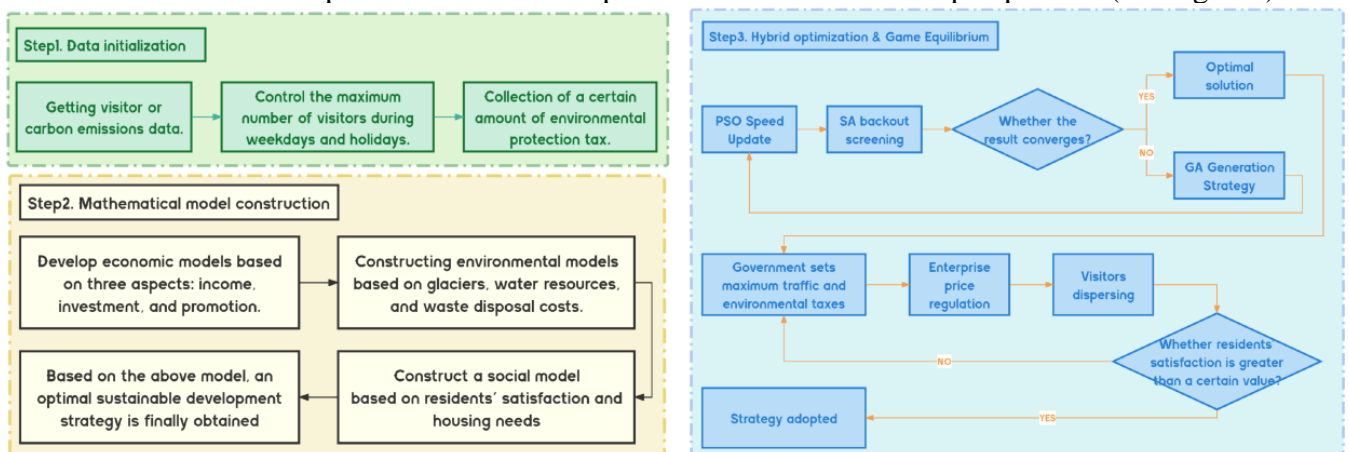


Figure 1. Flow Chart of Model Construction

### 2.2.1 Multi-objective optimization models

In order to comprehensively measure the level of sustainable tourism development, this study proposes the Sustainable Tourism Development Index (HDI) as the net economic benefit, which is quantified by the following formula:

$$W = \sum_t [R(t) - C_{env}(t) - C_{soc}(t) - C_{long}(t)] \quad (1)$$

The economic benefits of tourism  $R(t)$  can be considered from a number of perspectives, including local spending by tourists, government tax revenues from tourism activities, and revenues generated by related additional services. Can be considered from a number of perspectives, including local spending by tourists, government tax revenues from tourism activities, and revenues generated by related additional services. The concept of environmental costs  $C_{env}$  encompasses a wide range of environmental dimensions, including but not limited to glacier retreat, water overload and carbon emissions. The financial implications of glacier retreat are estimated through a combination of glacier area change and glacier value per unit area. The cost of water resource overload is determined by the amount of water usage and scarcity. The cost of carbon emission is calculated based on the carbon emission coefficients of various modes of transport and the number of tourists travelling. Social costs  $C_{soc}$  are defined as the quantifiable impact of resident satisfaction and infrastructure congestion. Resident satisfaction is scored by taking into account multiple dimensions, such as the economic benefits, environmental changes and quality of life impacts of tourism activities. By contrast, the cost of infrastructure congestion is assessed based on the relationship between tourist flows and the capacity of the infrastructure.

### 2.2.2 Hybrid intelligence algorithm (GA - PSO - SA)

The GA-PSO-SA hybrid intelligent algorithm employed in this study integrates the advantages of three algorithms: the Genetic Algorithm (GA), the Particle Swarm Optimization (PSO) and the Simulated Annealing (SA). The objective of this integration is to achieve efficient and accurate optimisation solutions.

The following pseudo-code implementation of the hybrid intelligent algorithm is shown in Table 1.

**Table 1.** Pseudo-code of Hybrid Intelligence Algorithm

Code Number	Code Content
1	Initialize population size $N=200$ , particle velocity $v \in [-0.1,0.1]$
2	while iterations $\leq 500$ do
3	Calculate the fitness $W$ and update the individual optimal pbest and global optimal gbest.
4	for each particle $i$ do
5	Update velocity: $v_i = 0.8v_i + 1.2r_1(pbest_i - x_i) + 1.5r_2(gbest - x_i)$
6	Update position: $x_i = x_i + v_i$ (boundary constraint: $V_{max} \in [2000,3500]$ )
7	Accept suboptimal solution with probability $P = \exp(-\Delta W/T)$ (initial temperature $T = 1000$ , cooling factor $\alpha = 0.95$ )
8	Execute an elite retention strategy to eliminate the lowest adapted 10% of individuals
9	end while

### 2.2.3 The Stackelberg game framework

In the decision-making process of sustainable tourism development, there are interactions and strategy choices between different interest subjects. In order to understand these interactions, this study introduces the Stackelberg game framework. In this framework, the government and enterprises are regarded as the two main game players. The government, as the leader, has the advantage of making decisions first and guiding the development direction of the tourism market by formulating tax and investment policies. Enterprises, as followers, adjust their pricing strategies according to the principle of maximizing their own interests after observing the government's decisions. Through this two-layer optimization mechanism, the strategic equilibrium between the various stakeholders in the

tourism market is achieved, thus providing effective policy support and market regulation for sustainable tourism development.

Specifically, when formulating policies such as environmental taxes and infrastructure investment ratios, the government must consider the impact on corporate behavior and the overall efficiency of the tourism market; enterprises, in turn, must take into account the cost changes brought about by government policies and the market's response to demand when formulating their pricing strategies. Through the continuous adjustment process, a stable equilibrium state is eventually reached, thereby enabling the tourism market to achieve coordinated development in economic, environmental and social aspects.

### 3. Modelling and solving

#### 3.1. Model constraints

In order to ensure the rationality and feasibility of the model, this study sets a series of strict constraints covering a wide range of environmental, social and policy aspects.

The environmental constraints on tourism in the glacier area of Juneau City are such that the maximum carrying capacity of the glacier area  $V_{\max, glacier}$  is set to ensure that the intensity of tourism activities will not exceed the ecological tolerance of the glacier area. Concurrently, a carbon emission threshold  $E_{safe}$  is established to regulate the environmental impact of carbon emissions from tourism activities, ensuring that these emissions remain within a safe range.

Social constraints: Resident satisfaction is recognized as a significant social indicator of sustainable tourism development. To ensure the quality of life of residents and their support for tourism, resident satisfaction is defined  $S(t) > S_{\min}$  with  $S_{\min}$  a predefined minimum acceptable level of resident satisfaction. Additionally, the issue of infrastructure congestion must be given due consideration, as excessive tourist traffic may overwhelm infrastructure. Consequently, the congestion cost of infrastructure is determined  $\kappa V_d(t) < C_{\max}$ , with the congestion cost coefficient  $\kappa$  representing the tourist flow rate  $V_d(t)$  and the maximum acceptable value of congestion cost of infrastructure  $C(\max)$  is established.

Policy Constraints: In terms of policy formulation, environmental taxes  $T_{env}$  and infrastructure investment ratios  $\gamma$  are constrained by practical operability and policy reasonableness. The range of values for the environmental tax is set at US\$ [10,20] per person, and the range of values for the infrastructure investment ratio is set at [20,30] per cent.

#### 3.2. Solution results

The subsequent results were obtained by solving the model by applying the Stackelberg game with the GA-PSO-SA hybrid intelligent algorithm:

Hybrid algorithm results: glacier area carrying capacity is 2,583 people/day. environmental tax is \$17/person, and infrastructure investment ratio is 24%.

The Stackelberg game equilibrium yields a glacier carrying capacity of 2,165 persons/day, an environmental tax of USD 19/person, and an investment ratio of 30%.

Further analysis reveals that the dynamic pricing coefficient increases from 0.15 in the hybrid algorithm solution to 0.2 in the game equilibrium solution. This finding suggests that governments should implement dynamic pricing strategies to optimise spatiotemporal tourist distribution through intensified price regulation, so as to alleviate the pressure of tourist peak periods and popular areas and achieve the optimal allocation of tourism resources.

### 3.3. Analysis of results

Strategy selection: Prioritize short-term economic development: choose the optimal solution of the hybrid algorithm (high tourist arrivals, low promotion costs), but be wary of the accumulation of hidden costs.

Focus on long-term sustainable development: adopt the equilibrium solution of Stackelberg’s algorithm (low carbon emissions, high infrastructure investment), complemented by complementary policies to compensate for short-term losses.

Differences in key parameters: Visitor capacity: the hybrid algorithm is close to the upper limit of the carrying capacity of the glacier area and focuses on short-term gains; Stackelberg limits the number of visitors through a game framework, reduces the risk of glacier retreat and internalizes hidden environmental costs.

Environmental protection tax: the hybrid algorithm is \$17 per person (moderately burdensome and undercompensates for implicit costs); Stackelberg raises the tax to \$19 per person and strengthens carbon constraints.

Infrastructure investment ratio: 24 per cent in the hybrid algorithm (low short-term financial pressure but high congestion costs); Stackelberg raises it to 30 per cent to alleviate congestion and pollution pressures, in line with long-term implicit risk management strategies.

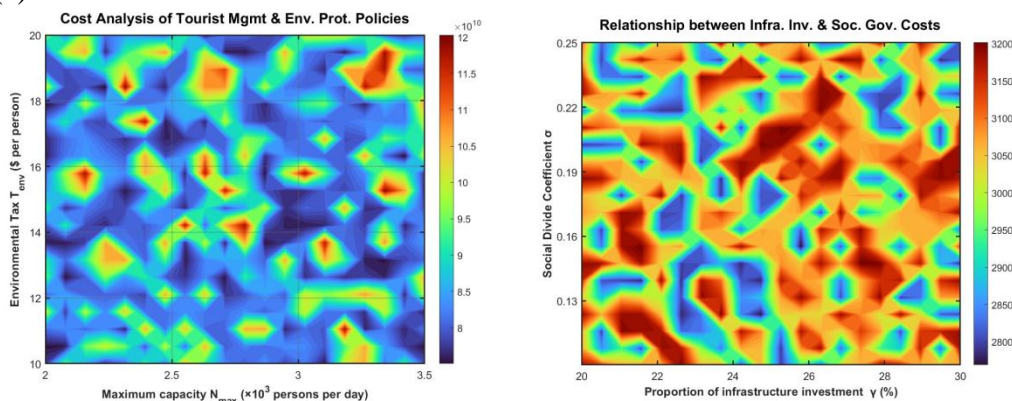
Dynamic pricing coefficient: 0.15 for the hybrid algorithm (companies rely on tourist volume growth to maintain revenue); Stackelberg increases to 0.2, companies respond to policy changes through price adjustments.

Promotion cost ratio: 34.5% in the hybrid algorithm (focusing on short-term benefits); Stackelberg increases to 39.76%, where companies increase promotion investment to offset the impact of high taxes and visitor restrictions.

Actual carbon emissions: 37,287.61 tons in the hybrid algorithm; Stackelberg significantly reduced to 32,057.49 tons through environmental taxes and visitor volume restrictions, but further optimization of policy instruments is still required.

### 3.4. Sensitivity analysis

In order to analyze the cost sensitivity of the environmental policy mix, the government’s controllable maximum carrying capacity,  $N_{max}$ , and the environmental tax,  $T_{env}$ , are selected as the analyzed dimensions. These two parameters correspond to the level of pressure and environmental governance inputs when directly affecting the ecosystem by means of tourist scale control and economic regulation, respectively. The subsequent analysis was conducted within the specified range of carrying capacity (2000-3500 people/day) and tax interval (10-20 \$/person). This culminated in Figure 2-(a).



(a) Cost Analysis of Tourist Mgmt & Env. Prot. Poli- (b) Relationship between Infra. Inv. & Soc. Gov. Costs

**Figure 2.** Sensitivity analysis heat map

For the two-factor-driven analysis of social costs, the proportion of infrastructure investment, represented by the parameter  $\gamma$ , and the social differentiation coefficient, denoted by  $\sigma$ , are initially selected. These parameters characterize the enterprise development strategy and the social structure characteristics, respectively, and collectively determine the structural changes of social costs. The analysis is then conducted within the range of an investment ratio of 20-30% and a social differentiation coefficient of 0.1-0.25, culminating in Figure 2-(b).

Elasticity of environmental taxes with respect to tourist density: for every  $1 \times 10^3$  increase in capacity/day, environmental taxes need to be raised by about \$0.8/person. Because the increase in tourist traffic leads to a rise in carbon emissions, the environmental costs need to be compensated by raising the environmental tax.

Analysis of the investment-benefit ratio: For every 1% increase in infrastructure investment, the social split coefficient decreases by 0.003 and the cost increases by 40 units. This leads to the conclusion that an increase in the investment ratio reduces the cost coefficient of congestion and thus indirectly reduces residential conflicts (Table 2).

**Table 2.** Summary of Sensitivity Analysis of Key Parameters

Parameter Name	Impact on W	Impact on E(t)	Impact on S(t)	Importance Level
Environmental Tax $T_{env}$	+8% to -12%	-15% to +10%	+5% to -8%	High
Infrastructure Investment Ratio $\gamma$	+10% to -5%	-8% to +5%	+12% to -6%	High
Tourist Density Coefficient $\beta$	-20% to +15%	+25% to -18%	-10% to +8%	Extremely High
Dynamic Pricing Coefficient $\eta_1$	+5% to -8%	-5% to +8%	+3% to -5%	Medium
Resident Conflict Penalty Coefficient $\sigma$	-12% to +5%	+3% to -5%	-15% to +10%	Medium
Glacier Retreat Critical Temperature $T_{crit}$	-10% to +8%	+12% to -10%	-5% to +3%	Medium

#### 4. Discussion

The model's primary advantage lies in its multi-dimensional coupled analysis, a significant advancement over the limitations of traditional single-objective research. By comprehensively considering objectives across multiple dimensions, including economic, environmental, and social factors, the model facilitates a comprehensive assessment of the integrated benefits of tourism development. This, in turn, provides a robust foundation for the formulation of more scientific and reasonable tourism policies. Furthermore, the model incorporates dynamic strategies, such as stepped retention tax and real-time pricing strategies, to enhance its efficacy. These dynamic strategies enable the flexible adjustment of policies and prices according to the actual situation of the tourism market, thereby achieving an effective balance in the distribution of tourism resources across different time periods and regions. Furthermore, the utilization efficiency of resources is enhanced, while simultaneously reducing the negative impacts of tourism activities on the environment and society. The model construction is based on extensive and accurate data sources and undergoes a rigorous data pre-processing process. This data-driven modelling approach enables the effective utilization of the information contained within the actual data, thereby enhancing the prediction accuracy and reliability of the model. Consequently, the model's results are rendered more convincing and practical in terms of their potential applications.

The model's limitations can be categorized as follows: first, the computational complexity is high due to the involvement of multiple complex algorithms and multi-objective co-optimization; second, the efficiency of the model in real-time decision-making scenarios is limited to a certain extent; third, further optimisation of the algorithm structure or the use of more powerful computing resources is required to improve the computational speed; and fourth, the accuracy of the model is highly dependent on high-quality input data. However, during the data collection process, deviations in local parameters may occur due to challenges in data acquisition, measurement errors, and other factors. These deviations can be amplified during the model calculation process, potentially impacting the accuracy and reliability of the model outputs. Consequently, the necessity for enhanced data quality control and uncertainty analysis in future research is evident.

## 5. Conclusion

The multi-objective optimization model proposed in this paper, with the help of intelligent algorithms and a gaming framework, successfully provides a comprehensive solution for the tourism industry of Juneau City that takes into account both economy and ecology. Through the implementation of a stepped tax and optimization of infrastructure investment, it is possible to effectively reduce carbon emissions by 14%, whilst simultaneously significantly improving the satisfaction of residents. The findings of this study offer a concrete decision-making basis for the city of Juneau in addressing the challenges associated with tourism development. Furthermore, the study provides a valuable reference point for other tourist destinations grappling with comparable issues.

In the future, the research can be expanded in two directions. Firstly, the model can be applied to other over-tourism regions worldwide, thus validating the versatility and effectiveness of the model by analyzing data from different regions and adapting the model accordingly. Secondly, the model can be combined with real-time data collection and transmission technology, the input data of the model can be constantly updated, thereby enhancing the model's dynamic responsiveness and enabling it to make timely adjustments to strategies in accordance with real-time changes in the tourism market. The incorporation of real-time changes in the tourism market allows for the timely adjustment of strategies, thereby better serving the practical needs of sustainable tourism development.

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