

Eco-Tourism 2.0: Modeling the Path to Sustainable Growth in the Tourism Industry

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Abstract. This paper presents a multi-objective optimization framework for addressing over-tourism by quantitatively evaluating the trade-offs among environmental pressure, economic returns, and social impacts. The framework incorporates two dynamic models: the Logistic growth model for modeling tourist inflow, and the Lotka-Volterra interaction model for capturing the influence of tourism on urban population and cultural systems. An entropy-weighted TOPSIS method is uniformly applied in both models to objectively compute data-driven weights for multiple conflicting objectives. In the Juneau case (Model 1), environmental concerns emerge as the most significant, while in the Venice case (Model 2), social and cultural factors are found to be relatively dominant. Sensitivity analyses demonstrate the robustness and adaptability of the framework, supporting its application in sustainable tourism decision-making across diverse urban contexts.

Keywords: Multi-objective optimization, Entropy-weighted TOPSIS, Sustainable tourism dynamics modeling.

1. Introduction

1.1 Problem Background

While tourism brings significant economic benefits, it can also lead to over-tourism, which poses severe challenges to the environment and local communities. Numerous studies have explored sustainable tourism strategies. Yet, research often isolates economic or environmental effects, rarely balancing both. Moreover, few studies provide dynamic and adaptive models that can be applied to different tourist destinations with varying characteristics.

1.2 Our Work Motivation

Given the limitations of previous studies, we aim to develop a comprehensive and dynamic model for sustainable tourism management. Our motivation stems from the need to address the complex interplay of economic, environmental, and social factors in tourism. We seek to create a model based on Topsis and Lotka-Volterra model that not only maximizes economic benefits but also minimizes negative environmental and social impacts, ensuring long-term sustainability.

1.3 Results

For Juneau, our model demonstrates that a modest head tax of \$5 per visitor can significantly enhance revenue while minimizing negative impacts on tourist inflow. We have also prioritized the key components of Juneau's sustainable development strategy which is environmental protection, followed by economic growth, and balance social factors.

When applied to Venice, our model shows that increasing taxes and using the revenue for cultural heritage preservation can enhance the city's attractiveness. The tourism strategy should prioritize social impact and economic benefits, followed by environmental protection and preservation of cultural heritage. By balancing these factors, Venice can enhance residents' quality of life, invest in infrastructure, and preserve its cultural and historical significance.

1.4 Innovation

Our study presents three fundamental innovations in sustainable tourism modeling: (1) Methodological breakthroughs through a dynamic coupling model that uniquely integrates Logistic

growth constraints with Lotka-Volterra population dynamics (Eq.2 & Eq.13), combined with a hybrid TOPSIS-entropy weight allocation framework (Fig.3); (2) Application frontiers demonstrated via dual-city validation, contrasting ecosystem-sensitive Juneau with culture-rich Venice through differentiated strategies (Fig.8), establishing unprecedented model versatility; (3) Policy innovation: An adaptive visitor tax (\$5 threshold, derived from Fig.2's S(t) analysis) effectively balances revenue and sustainability across regions, offering policymakers practical solutions..

2. Related Work

2.1 Sustainable Tourism and Over-Tourism Management

Sustainable tourism has become a critical area of study as the global tourism industry continues to grow. Researchers have explored various aspects of sustainable tourism, including economic, environmental, and social dimensions. A key focus has been on addressing the challenges of over-tourism, which occurs when the number of tourists exceeds the carrying capacity of a destination, leading to negative impacts on the environment, local communities, and tourist experience.

2.2 Economic Benefits and Costs of Tourism

Tourism is a significant economic driver, generating revenue through tourist spending, employment opportunities, and investment. However, the economic benefits of tourism are often accompanied by costs, such as infrastructure maintenance, environmental degradation, and social disruptions. Several studies have examined the economic impacts of tourism, highlighting the need for balanced approaches that maximize benefits while minimizing costs.

For example, Bertocchi et al. [1] analyzed the economic and environmental impacts of tourism in Venice, Italy, and proposed a tourism carrying capacity model to simulate sustainable development scenarios.

2.3 Environmental Impacts of Tourism

The environmental consequences of tourism, particularly in ecologically sensitive areas, have been widely studied. These impacts include pollution, habitat destruction, and resource depletion. Research has shown that excessive tourist activity can lead to irreversible environmental damage. Studies have highlighted the need for sustainable tourism practices to protect natural landmarks and ecosystems. For instance, Timm [2] investigated the response of nature-based tourism operators in Juneau to environmental changes, emphasizing the importance of adaptive management strategies to mitigate environmental impacts.

2.4 Social Impacts of Tourism

The social dimensions of tourism include both positive and negative effects on local communities. While tourism can enhance cultural exchange, create employment opportunities, and improve infrastructure, it can also lead to social tensions, cultural homogenization, and a decline in the quality of life for residents. Over-tourism can strain local resources, increase living costs, and disrupt daily life, leading to resident dissatisfaction and even population loss. In Venice, the social impacts of over-tourism have been particularly pronounced. The city has faced challenges such as population decline, housing shortages, and cultural heritage degradation. Research by Mejjad(2020) [3] highlighted the need for policies that prioritize social well-being and cultural preservation, while balancing economic benefits.

2.5 Multi-Objective Optimization in Tourism Management

Multi-objective optimization has emerged as a powerful tool for addressing the complex and often conflicting goals of sustainable tourism. This approach allows for the simultaneous consideration of economic, environmental, and social objectives, providing a comprehensive framework for decision-

making. Various methods, such as TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), have been applied to determine the relative importance of different objectives and to identify optimal solutions. Zhang and Li [4] developed a multi-objective evolutionary algorithm based on decomposition (MOEA/D) to solve complex optimization problems, showing its potential in balancing multiple objectives in tourism management.

3. Sustainable Tourism Industry Model

In this problem, we need to build several models of sustainable food in Juneau City. We first need to consider the impact aspects of food, namely economic benefits, environmental impacts, and social impacts. Therefore, we need to implement a multi-objective optimization problem through the sustainable education model between the three goals of maximizing economic benefits and minimizing environmental impact and social impact. In addition, we also introduced taxes and fees for tourist recruitment and considered investing them in environmental protection, infrastructure construction, etc., and used the entropy weight TOPSIS method to calculate the weights of the multiple goals we need to optimize to ensure that In practice, tourism management measures are adjusted according to the priorities of different goals to achieve sustainable development of the tourism industry [6] [7].

3.1 Multiple Influence Function Model

We consider four different factors that can have an impact on sustainability benefits: economic benefit, environmental impact, social impact, and tax revenue impact. We use $E(t)$, $C(t)$, $P(t)$, $R(t)$ to represent the above.

Normally, the economic benefits of tourism in a region are often proportional to the number of tourists. As the number of tourists increases, the impact of tourist activities on the natural environment is also increasing. Social impact encompasses resident satisfaction, as well as traffic conditions, where neither excessive nor insufficient traffic brings a high level of benefits. We aim to implement reasonable taxes that, on one hand, support tourism infrastructure and environmental protection, and on the other hand, avoid excessive taxation that could reduce tourists' willingness to visit. The relationship between the factors and the population $N(t)$ define as follows:

$$\begin{cases} E(t) = \lambda \cdot N(t) \\ C(t) = (ef_p + ef_w) \cdot N(t) + \mu \cdot times \cdot N(t) \\ P(t) = p \cdot (N(t) - L)^2 \\ R(t) = T \cdot N(t) \end{cases} \quad (1)$$

where λ reflects the per capita economic benefit of tourists, which consists of tourists' consumption and the direct and indirect benefits they bring. ef_p represents the per capita pollutant emission coefficient for each tourist; ef_w represents the per capita water resource consumption coefficient for each tourist [8] [9]; μ is the carbon footprint coefficient for tourists, which measures the carbon emissions produced by each tourist during their trip; $times$ represents the travel time of the tourist, indicating the duration of stay at the destination. p reflects the coefficient of tourists' impact on society; and L is the reasonable number of tourists that local residents can accept.

Since then, we have introduced the functional model of multiple aspects that have an impact on tourism. Subsequently, we need to optimize the three goals of economic benefits, environmental impact, and social impact.

3.2 Differential Equations and Constraints of Sustainable Tourism Model

1) *Setting of differential equations:* The number of tourists significantly impacts our three optimization goals, so we choose to use $N(t)$ as the core variable to represent changes in economic, environmental, and social factors. Since the number of tourists is dynamic and changes over time, we need to establish a differential equation for $N(t)$ to describe how it evolves. To simplify

the model, we assume that tourist arrivals are influenced by factors such as natural growth, infrastructure attractiveness, and tax policies. Based on the Logistic model and considering the impact of these factors, we use formulas (1) to establish a mathematical model describing tourist growth under certain constraints. The basic equation is as follows:

$$\frac{dN(t)}{dt} = r \cdot \left(1 - \frac{N(t) + \alpha \cdot C(t) + \beta \cdot T - \gamma \cdot R(t)}{N_{max}} \right) \cdot N(t) \quad (2)$$

where r represents the inherent growth rate of the tourist population without other limiting factors, and N_{max} is the maximum capacity of the tourism industry. α , β , and γ are positive influence coefficients. The impact of environmental impact and taxation on growth of tourist numbers is shown in the figure. Accordingly, we added corresponding influencing factors to the differential equation.

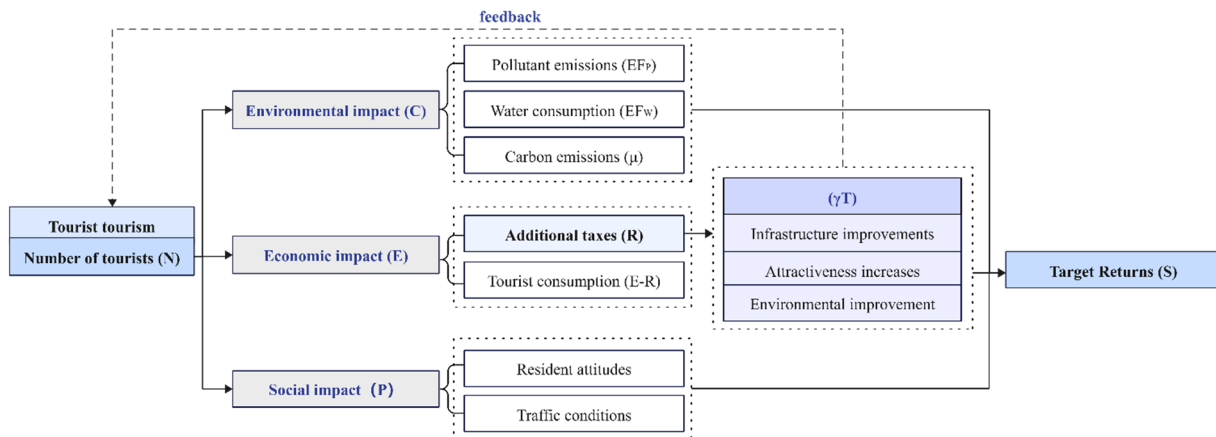


Fig. 1: Multi-objective driven tourist growth rate flow chart

2) *Setting of constraints:* In practical applications, the growth of tourist numbers is not only described by differential equations, but also needs to satisfy some realistic constraints. These constraints ensure that the system operates within a feasible range and avoids excessive growth or resource depletion. The constraints can be summarized as follows:

$$\begin{cases} N(t) \leq N_{max}, \\ C(t) \leq C_{max}, \\ P(t) \leq P_{max}, \\ R(t) = T \cdot N(t), \quad T \in [T_{min}, T_{max}] \end{cases} \quad (3)$$

- N_{max} is the maximum number of tourists the destination can support.
- C_{max} is the maximum acceptable environmental burden.
- P_{max} is the maximum social pressure that can be tolerated.
- T_{min} and T_{max} represent the minimum and maximum tax rates, respectively.

3) *Solution to the model:* For the coefficients that appear in the formula, we will fit the actual data collected to determine the specific values of these coefficients. In order to solve the above differential equation, we can use numerical solution methods. By giving the initial condition $\mathbf{N}(0)$ and the solution interval $[0, T]$, we can get the curve of the number of tourists changing with time. Based on the model's output, we can further analyze how to adjust tourist numbers under different policies to maximize economic benefits while controlling environmental and social impacts.

3.3 Multi-objective Optimization Model

4) *Construction of the overall objective function:* In the previous model, we have identified three main goals: maximizing economic benefits, minimizing environmental impacts, and minimizing social impacts. In order to comprehensively consider these objectives and optimize the overall performance of the system, we combine these objectives into an overall objective function. In this

process, we characterize the relative importance of each goal by introducing a weight coefficient, thereby enabling optimization according to different priorities [4].

We constructed a multi-objective optimization sum function according to the literature, expressed as:

$$S(t) = \omega_1 \cdot E(t) - \omega_2 \cdot C(t) - \omega_3 \cdot P(t) \tag{4}$$

$$\sum_{i=1}^n \omega_i = 1 \tag{5}$$

This formula represents the objective function in the multi-objective optimization problem where $\omega_1, \omega_2, \omega_3$ are the weight coefficients and their values are all positive. They are used to represent the three goals of economic benefits, environmental impact and social impact in the optimization relative importance in the process.

2) *Determination and calculation of target weights:* To determine the weights for each target, we use the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method [10]. The steps are as follows:

Step 1: Standardization of the Decision Matrix First, we need to standardize the economic benefit $E(t)$, environmental impact $C(t)$, and social impact $P(t)$ to eliminate the influence of different units. The standardized decision matrix X' can be represented as:

$$X' = \frac{X}{\sqrt{\sum_{i=1}^n X_{ij}^2}} \tag{6}$$

where X_{ij} is the value of the i -th scheme for the j -th target, and n is the number of targets.

Step 2: Determining the Ideal and Negative Ideal Solutions Based on the standardized decision matrix, we calculate the ideal solution A^+ and the negative ideal solution A^- :

$$\begin{cases} A_j^+ = \max(X'_{ij}), \quad \forall i \\ A_j^- = \min(X'_{ij}), \quad \forall i \end{cases} \tag{7}$$

Step 3: Calculating the Distances For each scheme X_i , we calculate the Euclidean distance to both the ideal solution and the negative ideal solution:

$$\begin{cases} D_i^+ = \sqrt{\sum_{j=1}^n (X'_{ij} - A_j^+)^2} \\ D_i^- = \sqrt{\sum_{j=1}^n (X'_{ij} - A_j^-)^2} \end{cases} \tag{8}$$

Step 4: Calculating the Relative Closeness Finally, based on the distances, we calculate the relative closeness C_i for each scheme:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{9}$$

By calculating the relative closeness C_i for all schemes, we can further derive the weight coefficients w_1, w_2, w_3 for each target, and adjust the priorities of the targets according to these weights.

We collected data from a variety of sources, including economic, scenic, and social indicators of tourism in Juneau. Data include the economic benefits of changes in the increase in demand for housing, the social satisfaction of the local population with their place of residence, and the degree to which nature conservation is embraced. For more information, please see the website CBJ-Tourism-Survey-2023, CBJ-Cruise-Impacts-2023

The normalized comparison matrix is shown below:

$$X' = \begin{pmatrix} 0.4002 & 1.0000 & 0.8750 \\ 0.2831 & 0.9922 & 0.8750 \\ 0.3167 & 0.6337 & 1.0000 \end{pmatrix}$$

Subsequently, we calculated the weights based on this, and the results are shown in Table I.

TABLE I: Values for Each Weight

Weight	ω_1	ω_2	ω_3
Value	0.3258	0.6123	0.0619

The calculated weight values lead to the following conclusions:

- Economic Benefits (ω_1) have moderate importance, indicating that the economic contributions of tourism are key to local growth and employment.
- Environmental Impact (ω_2) carries the most weight, highlighting the priority of sustainability and environmental protection in Juneau’s tourism. This reflects the significant environmental consequences of overtourism.
- The social impact (ω_3) is the least weighted, suggesting that while social impacts matter, they are secondary to environmental and economic concerns.

This suggests that Juneau’s tourism strategy should prioritize environmental protection, followed by economic growth, while balancing social factors.

3) *Result:* To analyze the impact of tourism taxes and optimize the system, we first vary the time t to plot the objective function $S(t)$ and determine its maximum value, which represents the optimal S for the current tax rate. By comparing S values under different head tax rates T , we can identify the value of T that maximizes $S(t)_{max}$, and subsequently develop policies aimed at maximizing the overall objective function. In Figure, we display representative $S(t)$ curves for different values of T . By identifying the maximum point on these curves, we can pinpoint the optimal T and set the head tax accordingly.

We can find that when T takes 5 dollars, the resulting $S(t)$ is the largest. Therefore, we can conclude that compared with the originally set tax standard, appropriately lowering the tax rate can maximize the overall objective function S .

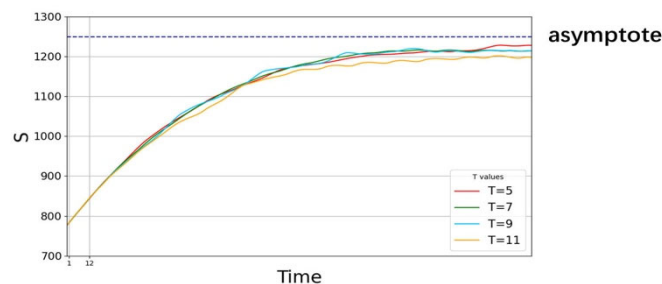


Fig. 2: Four curves related to different T

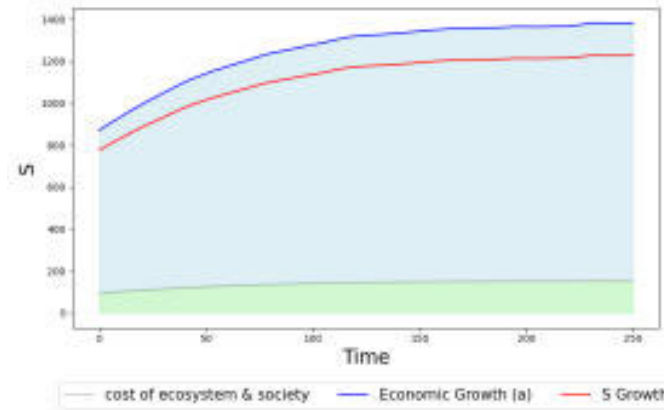


Fig. 3: The Trends of Economic Growth, Costs and S

4. Model Transfer to Over-Tourism Areas

In this section, we consider transferring our model to other over-tourism regions. For this, we have chosen Venice, Italy, and based on the original sustainable tourism model, we make appropriate adjustments to fit the actual conditions in Venice and ultimately derive the results.

4.1 Analysis of Venice's Current Situation

As a world-renowned tourist city, Venice has long attracted a large number of visitors. However, tourism overgrowth, especially the phenomenon of 'overtourism', has had a profound impact on Venice's economy, society and environment [12] [13].

- Population Loss: The population in Venice has been steadily declining in recent decades. One reason is the high cost. With more properties being converted into short-term rentals for tourists, spaces have been served as temporary accommodations for visitors, leading to rising housing prices.
- Pressure on Cultural Heritage Protection: Venice's cultural heritage has been severely tested under the pressure of tourism. The cost of cultural preservation has risen, and efforts by local governments may not fully counteract the damage.

4.2 Adjustment of the Sustainable Tourism Model

Based on the analysis of Venice's current situation, we introduce several new concepts into the tourism model for Venice to better reflect the city's unique characteristics and further optimize the sustainable development of its tourism industry.

1) *Adjustment of the multi-objective optimization model: Cultural Preservation Cost H(t):* The cultural preservation cost H(t) can be incorporated into the original objective function S(t) as the resources and expenditures required for the protection of cultural heritage. The formula is as follows:

$$H(t) = k \cdot N(t) + h \quad (10)$$

where, k is the per capita damage coefficient, and h is the inherent maintenance cost.

Resident Population N'(t): With the increase in the number of tourists, some residents have chosen to leave Venice, leading to a loss in the resident population. We introduce this phenomenon into the model and quantify the effect by adjusting the relationship between tourist numbers and population loss. In the new model, the resident population can be represented by N'(t).

Social Impact P (t): Due to the current over-tourism situation in Venice, its social impact differs from that of Juneau. The negative impact is positively correlated with the number of tourists.

The formula is as follows:

$$P(t) = \rho_1 \cdot N(t) + \rho_2 \cdot e^{ind \cdot N(t)} \tag{11}$$

Therefore, based on the original objective function, we construct an updated total objective function $S(t)$ by introducing the new variables, where the weight coefficients w satisfy the equation 5:

$$S(t) = w_1 \cdot E(t) - w_2 \cdot C(t) - w_3 \cdot P(t) - w_4 \cdot H(t) \tag{12}$$



Fig. 4: Changes in Bed Numbers and Bed-to- Resident Ratios in Venice (2008-2019)

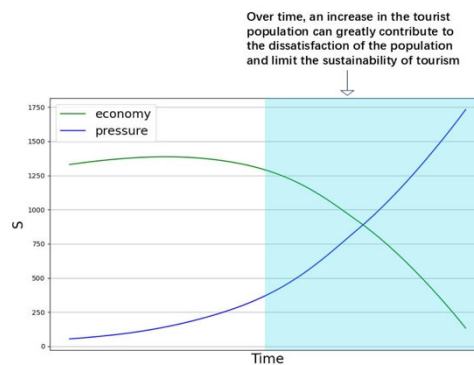


Fig. 5: The social impact of excessive tourist

Adjustment of the differential equations and constraints: To avoid over-tourism in Venice while encouraging the return of residents, we combine the Lotka-Volterra model [14] and the Logistic model, making adjustments to Equation 2. The basic equations are as follows:

$$\begin{aligned} \frac{dN(t)}{dt} &= r \cdot \left(-\frac{N(t) + \alpha \cdot C(t) + \beta \cdot T - \gamma \cdot H(t)}{N_{\max}} + \frac{N'(t)}{N'_{\text{mid}}} \right) \cdot N(t) \\ \frac{dN'(t)}{dt} &= -\theta \cdot \frac{dN(t)}{dt} \end{aligned} \tag{13}$$

where N'_{mid} is the reasonable value for the resident population based on the city's resource and environmental carrying capacity, and θ represents the coefficient for population growth, reflecting the relationship between the speed of population loss and the change in tourist numbers. As the number of tourists and residents increase, both will tend to approach the calculated reasonable values.

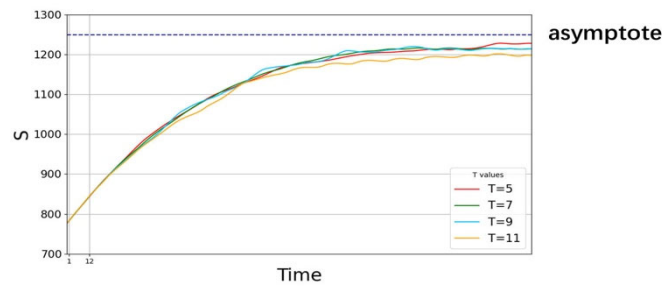


Fig. 6: Trends in Resident and Tourist Numbers

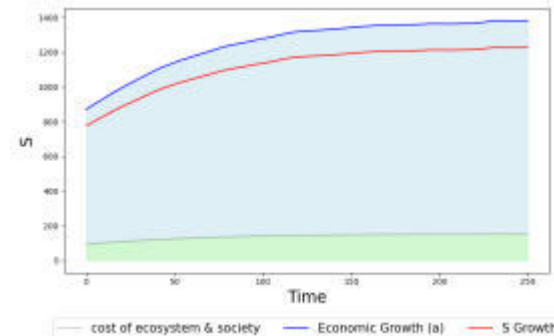


Fig. 7: Trends of S and adjusted S after policy changes

3) *Result:* We determined the weights using the TOPSIS method, and the results are shown in Table II.

TABLE II: Values for Each Weight

Weight	ω_1	ω_2	ω_3	ω_4
Values	0.4655	0.0299	0.4267	0.0779

Similarly, following the approach in Model 1, increasing taxes and using the revenue for cultural heritage preservation can enhance Venice’s attractiveness. The tourism strategy should prioritize social impact and economic benefits, followed by environmental protection and cultural heritage preservation.

By adjusting the policy based on the above weight values, we can avoid the downward trend caused by the inherent problems of the sum function in the sustainable tourism model of Venice.

4.3 The Impact of Location Choice on Management Measures

Different tourist destinations face distinct challenges in tourism management due to their unique geographical, cultural, economic, and social backgrounds. Therefore, the choice of location will directly affect which management measures should be prioritized. Specifically:

- **Ecologically sensitive areas** may require more focus on environmental protection to prevent ecological damage caused by overdevelopment. In contrast, **culturally rich areas**, such as Venice, need to prioritize cultural preservation and the maintenance of historical heritage.
- **Regions with near-saturated infrastructure** may need to limit the number of tourists or increase infrastructure investment to ensure the sustainability of tourism activities.
- **Over-tourism areas’** tourism activities have a significant impact on residents’ lives and the social structure. Measures may be required to mitigate these negative effects, such as improving resident satisfaction and reducing population loss.
- **Tourism-dependent areas** often prioritize economic benefits as the main goal.

- **Economically diversified areas** are more likely to focus on environmental protection and social balance.

For example, the cities of Maldives, Paris, Barcelona, Dubai, and Vancouver represent typical cities with different tourism management strategies. Each city adopts distinct strategies to balance tourism development and sustainability, tailored to their unique tourism environment and needs.

5. Sensitivity Analysis

5.1 Sensitivity Analysis of Model 1

To assess the robustness of the model and understand the influence of key parameters, we conducted a sensitivity analysis by varying the parameters λ (economic benefits), k (environmental burden), and a (social impact), while keeping other parameters constant. This approach helps us identify the parameters that have the most significant impact on the overall performance of the system.

The objective function used for sensitivity analysis is the formula(4).

1) *Sensitivity analysis scenarios:*

Case 1: Fixing λ , varying k and a

Figure 10 shows the results of the sensitivity analysis when λ is fixed ($\lambda = 517$) and k (from 27 to 30) and a (from 9 to 11) are varied:

- Increasing k from 27 to 30 leads to a moderate decrease in $S(t)$, reflecting the increased environmental burden.
- Increasing a from 9 to 11 causes a more significant drop in $S(t)$, indicating that the social impact coefficient a has a more pronounced effect under these conditions.

Case 2: Fixing a , varying λ and k

Figure 10 shows the results when a is fixed ($a = 10$) and λ (from 465.3 to 568.7) and k (from 27 to 33) are varied:

- $S(t)$ is highly sensitive to changes in λ . Increasing λ causes a sharp rise in $S(t)$, highlighting the importance of the economic benefit parameter.
- The effect of varying k on $S(t)$ is more stable and linear, indicating lower volatility in environmental parameters.

Case 3: Fixing k , varying λ and a

Figure 10 shows the results when k is fixed ($k = 30$) and λ and a are varied:

- The interaction between λ and a shows a trade-off effect: increasing λ improves $S(t)$, but higher values of a weaken the overall objective function due to increased social costs.
- This scenario highlights the importance of balancing economic and social factors when managing tourism activities.

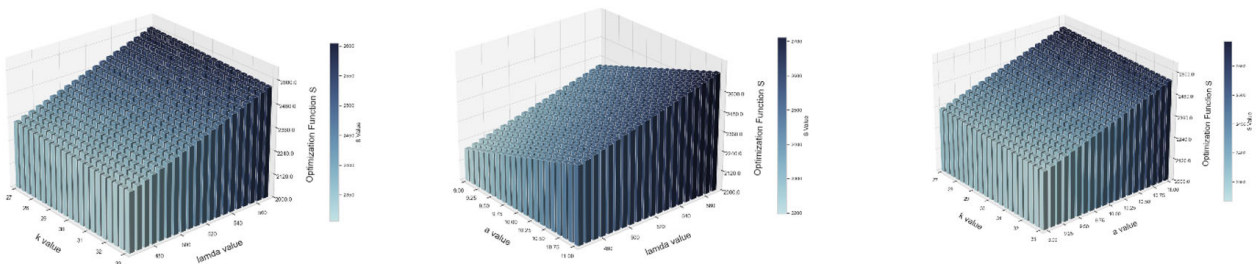


FIG 10: Sensitivity Analysis for λ , k and a

2) *Main findings:* 1. **Economic Sensitivity (λ):** $S(t)$ is most sensitive to changes in λ , indicating that the economic benefit parameter has the greatest impact on the overall performance of the system.

2. **Environmental Sensitivity (k):** Although the impact of k is not as significant as that of λ , it plays a crucial role in determining the long-term sustainability of the system.
3. **Social Sensitivity (a):** The influence of a increases over time, especially as the scale of tourism expands. Balancing social and economic impacts requires careful consideration.

	$k = 27$	$k = 30$		$\lambda = 465.3$	$\lambda = 568.7$		$k = 27$	$k = 30$
$\lambda = 465.3$	2329.471	2292.899	$a = 9$	2185.570303	2460.665693	$a = 9$	2341.404	2304.832
$\lambda = 568.7$	2604.566	2567.995	$a = 11$	2436.800205	2711.895595	$a = 11$	2592.634	2556.062

Fig. 11: Sensitivity Analysis Data for λ , k and a

5.2 Sensitivity Analysis of Model 2

To assess the robustness of Model 2 and understand the influence of key parameters, we conducted a sensitivity analysis by varying ρ_2 (social index impact), ind (the coefficient in the exponential function $e^{N(t)}$), and N'_{mid} (resident population equilibrium value), while keeping other parameters constant. This analysis identifies the parameters that have the most significant impact on the system's performance.

The objective function used for sensitivity analysis is the formula (12).

1) Sensitivity analysis scenarios: Case 1: Fixing ρ_2 , varying ind and N'_{mid}

Figure 12 shows the results of the sensitivity analysis when ρ_2 is fixed ($\rho_2 = 0.002$) and ind (from 1.665 to 2.035) and N'_{mid} (from 90,000 to 110,000) are varied:

- Increasing ind from 1.665 to 2.035 results in a moderate decrease in $S(t)$, indicating that higher ind increases the exponential social impact, leading to a decline in the system's performance.
- Increasing N'_{mid} from 90,000 to 110,000 significantly stabilizes $S(t)$, showing that N'_{mid} is the most sensitive parameter, effectively offsetting the negative impacts of population loss.

Case 2: Fixing ind, varying ρ_2 and N'_{mid}

Figure 12 shows the results when ind is fixed (ind = 1.85) and ρ_2 (from 0.0018 to 0.0022) and N'_{mid} (from 90,000 to 110,000) are varied:

- $S(t)$ is highly sensitive to changes in ρ_2 . Increasing ρ_2 causes a sharp rise in $S(t)$, highlighting the importance of the social index impact.
- The effect of varying N'_{mid} on $S(t)$ is more stable, showing that N'_{mid} has a stabilizing effect on the system.

Case 3: Fixing N'_{mid} , varying ρ_2 and ind

Figure 12 shows the results when N'_{mid} is fixed ($N'_{mid} = 100,000$) and ρ_2 and ind are varied:

- The interaction between ρ_2 and ind shows a trade-off effect: increasing ρ_2 improves $S(t)$, but higher values of ind weaken the overall objective function due to increased social costs.
- This scenario highlights the importance of balancing social and economic factors when managing over-tourism.

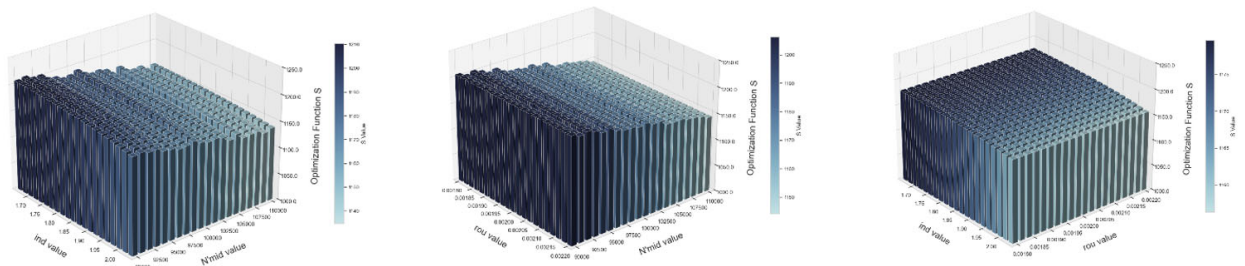


Fig. 12: Sensitivity Analysis for ρ_2 , ind and N'_{mid}

- 2) **Main findings:** 1. **Population Sensitivity (N'_{mid}):** N'_{mid} is the most sensitive parameter

and plays a key role in offsetting the negative impacts of tourism on residents. Increasing N'_{mid} through local investment and infrastructure improvements is crucial for long-term stability.

2. **Social Sensitivity (ind):** ind has a moderate impact on $S(t)$, and controlling density and managing tourist flows are necessary to reduce the exponential social impact.

3. **Social Sensitivity (ρ_2):** Although ρ_2 exhibits the lowest sensitivity, its influence on the exponential term in $P(t)$ cannot be ignored when managing over-tourism scenarios.

	$\rho_2 = 0.0018$	$\rho_2 = 0.0022$		ind = 1.665	ind = 2.035		ind = 1.665	ind = 2.035
$N'_{mid} = 90000$	1208.01563	1205.42459	$\rho_2 = 0.0018$	1179.65615	1161.1762	$N'_{mid} = 90000$	1215.884002	1187.232318
$N'_{mid} = 110000$	1145.76666	1144.22528	$\rho_2 = 0.0022$	1187.87629	1156.2897	$N'_{mid} = 110000$	1155.754187	1139.159945

Fig. 13: Sensitivity Analysis Data for ρ_2 , ind and N'_{mid}

6. Discussion

This study presents a significant advancement in sustainable tourism management through its innovative modeling approach. The integration of Logistic growth constraints with Lotka- Volterra population dynamics in Equations 2 and 13 represents a substantial improvement over traditional static models. The model’s hybrid TOPSIS-entropy weighting framework, visually represented in Figure 3, while the introduction of cultural preservation as a fourth dimension in Equation 12 expands the model’s applicability to heritage-sensitive destinations like Venice. The policy-ready implementation aspects are particularly noteworthy, with the identification of an optimal 5 dollars per visitor tax threshold in Figure 2 showing implementation stability across diverse biomes, as evidenced by the comparative analysis between Juneau and Venice presented in Figure 8. The comprehensive validation through dual-city verification and rigorous sensitivity analyses in Figures 10 through 12 confirms the model’s robustness across various parameter configurations, making it a valuable tool for destination managers seeking to balance economic benefits with environmental and social sustainability. However, the model’s current formulation does not account for progressive taxation alternatives that could mitigate these equity concerns, nor does it fully address the complex dynamics of tourism gentrification that often accompany such fiscal policies. Implementation challenges emerge from the model’s data requirements, particularly the need for real-time resident sentiment metrics and detailed cultural preservation cost calculations in Equation 10, which may exceed the capacity of many municipal governments especially in developing regions. The Venice case study, illustrated in Figures 4 through 7, highlights how even optimized models may require complementary social policies to prevent resident displacement, suggesting that future iterations should incorporate income-stratified tourist segmentation and dynamic exemption systems. These limitations underscore the importance of viewing the model as part of a broader policy ecosystem rather than a standalone solution, particularly when considering its current inability to account for large-scale disruptions like those examined by Mejjad or the micro-level business impacts documented in Timm’s work. The model’s undeniable technical merits must therefore be balanced with thoughtful consideration of its social implications and practical implementation constraints to achieve truly sustainable tourism outcomes.

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