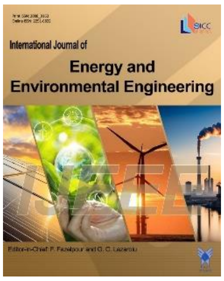

Volume 15, Issue 2, (2024) Article 10

International Journal
of
Energy and Environmental Engineering (IJEEE)

https://doi.org/10.57647/ijeee.2024.1502.10

The STMO Model for Balancing Growth and Conservation in Juneau, Alaska

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Original Research

Abstract

Juneau, Alaska, faces rapidly increasing visitor numbers, generating substantial economic gains while intensifying environmental pressures and social tensions. To address these challenges, this study develops a dynamic multi-objective optimization model that jointly considers economic revenue, ecological degradation, and social carrying capacity. The model integrates feedback loops and reinvestment strategies, demonstrating how visitor caps, tax policies, and targeted expenditures influence long-term system outcomes. Sensitivity analysis and simulation results identify the parameters most critical to sustainable tourism management, including infrastructure efficiency, environmental mitigation rates, and community development investment. Although Juneau serves as the case study, the framework is generalizable and can be adapted to other overtourism destinations by calibrating site-specific constraints and priorities. The findings highlight actionable pathways for balancing growth and conservation, while offering methodological and policy insights that extend to the field of overtourism research globally. Although the literature on overtourism has examined economic, social, and environmental impacts, it lacks a dynamic, multi-objective framework capable of capturing feedback loops and long-term trade-offs. Existing models are largely static or single-dimensional, leaving destinations without tools to understand how economic, social, and environmental outcomes interact over time. This study fills that gap by introducing a dynamic optimization model integrating revenue generation, ecological degradation, and social carrying capacity, offering a comprehensive structure for long-term sustainable tourism planning.

Keywords: Sustainable tourism; overtourism; Juneau, multi-objective optimization; dynamic feed-back; sensitivity analysis; reinvestment strategies; tourism management

Cite this article: Wang J., Yu Z., Li J., Shang Y., Lin H., The STMO Model for Balancing Growth and Conservation in Juneau, Alaska. Int. J. Energy Environ. Eng. 2024; 15(1) : 1-18 https://doi.org/10.57647/ijeee.2024.1502.10

1. Problem Restate

Tourism plays a central role in Juneau's economy, with the city receiving a record 1.6 million cruise passengers and $375 million in tourist-related revenue in 2023. However, this rapid influx of visitors has also intensified environmental pressures including accelerated glacier recession, waste management challenges, and localized pollution while contributing to social issues such as congestion, noise, and reduced quality of life for residents. Although measures such as visitor fees, hotel taxes, and cruise ship caps have been introduced, evaluating their long-term effectiveness requires a systematic approach that accounts for hidden economic, environmental, and social trade-offs. Despite substantial research on overtourism, most existing studies focus on short-term financial gains or single-dimension carrying-capacity models. These approaches often overlook the long-term, dynamic interactions among tourist flows, infrastructure strain, social tolerance, and cumulative environmental degradation. This leaves a critical research gap: the overtourism literature lacks a dynamic, multi-objective framework capable of modelling how tourism policies interact over time through feedback effects, reinvestment decisions, and changes in visitor behaviour.

To address this gap, the present study asks the following research question:

How can a dynamic optimization model balance economic benefits, environmental quality, and social carrying capacity to guide sustainable tourism policy in overtourism destinations such as Juneau?

By developing and analyzing such a model, the study seeks not only to provide actionable policy tools for Juneau but also to contribute a generalizable methodological framework for overtourism research.

Research Gap and Contribution

1. Overtourism has been widely examined from economic, sociocultural, and environmental perspectives. However, three key limitations persist in existing literature:
2. Short-term focus: Many studies prioritize immediate economic gains without accounting for how tourism impacts accumulate over time.
3. Single-dimensional analysis: Traditional models often analyze environmental or social impacts in isolation rather than integrating them into a unified, systems-based framework
4. Lack of dynamic modeling: Few approaches incorporate feedback loops, reinvestment mechanisms, or demand elasticity elements that fundamentally shape long-term sustainability outcomes.

This study addresses these limitations by introducing a dynamic, multi-objective optimization model that integrates economic, environmental, and social dimensions into a cohesive analytical framework. The model incorporates visitor demand elasticity, infrastructure evolution, environmental costs, and social carrying capacity, allowing policymakers to assess how present decisions influence future system conditions.

The contributions of this study are fourfold:
1. A novel dynamic framework that captures time-dependent feedback among tourism growth, environmental degradation, and social tolerance.
2. A multi-objective optimisation model that enables policymakers to balance revenue generation with sustainability constraints.
3. A reinvestment-based policy mechanism showing how tax revenue can be strategically allocated to infrastructure, environment, and community needs.
4. A generalizable theoretical structure that can be adapted to other overtourism destinations by calibrating site-specific parameters.

Together, these contributions fill a methodological gap in overtourism research and offer practical guidance for long-term destination management.

The STMO model integrates environmental engineering and resource management parameters by linking visitor numbers, environmental quality, infrastructure capacity, and community tolerance through a dynamic multi-objective optimisation framework. It models environmental degradation from tourism as a function of visitor volume and the load placed on engineered systems, while restoration investments offset these impacts based on their technical efficiency. Infrastructure capacity evolves through reinvestment-driven upgrades, and social carrying capacity increases as community pressures are reduced through targeted spending. These environmental, infrastructure, and social components shape visitor demand over time, producing feedback loops that reveal how tax policies, visitor caps, and reinvestment strategies influence sustainability trade-offs. By evaluating long-term economic, environmental, and social outcomes, the model identifies balanced growth–conservation scenarios suited to Juneau's unique ecological and infrastructural constraints.

2. Model Assumptions and Key Variables

2.1. Basic Assumptions

1. **Tourist demand is both price- and environment-sensitive.** Increasing fees or taxes can reduce the demand for visits, while deteriorating environmental quality (e.g., receding glaciers, pollution) can discourage future tourists. The elasticity of demand with respect to price and environment will affect visitor numbers.
2. **Local infrastructure has limited capacity.** There exists a threshold (e.g., maximum daily or annual **visitors**) beyond which additional costs and significant negative impacts on local facilities (e.g., waste management, water supply) escalate, leading to congestion and reduced service quality.

3. **Environmental degradation is linked to carbon emissions and other forms of pollution.** Cruise ships, **flights**, and various tourist activities generate emissions and pollution, which can accumulate over time, leading to long-term environmental consequences such as resource depletion, habitat disruption, and worsening air quality.
4. **Social carrying capacity is finite.** Residents can tolerate only a certain volume of tourists and tourist-related behaviors (e.g., overcrowding, noise).

Once this threshold is exceeded, dissatisfaction, local protests, and potential social unrest may arise, reducing overall social welfare and diminishing residents' quality of life.

5. **Reinvestment in sustainability measures can mitigate negative impacts.** A portion of tourism revenue (e.g., taxes or fees) should be allocated to sustainability measures, such as environmental protection, infrastructure improvements, and community development projects. These investments can help mitigate the negative impacts of tourism and promote long-term social acceptance and environmental health.

2.2 Key Variables and Parameters

Table 1. Key Variables and Parameters
① Core Variable, ② Cost/Capacity Variable, ③ Dynamic Feedback Parameter, ④ Elasticity Parameter.

Type	Symbol	Description
①	$x(t)$	Number of visitors (or cruise ship arrivals) in period t. This is a key driver for both revenue generation and environmental/social impacts.
①	$R(x, t_{\text{tax}})$	Total tourism revenue in period t, calculated as $[p_0 + t_{\text{tax}}] \cdot x(t)$, where p_0 is baseline per-visitor spending (in dollars) and t_{tax} is the per-visitor tax or fee. This represents the economic revenue generated from tourism.
①	t_{tax}	Per-visitor tax or fee (e.g., environmental levy, head tax). The value of t_{ax} will influence the visitor demand and tourism-related revenue.
①	p_0	Baseline per-visitor spending, excluding taxes or fees. This reflects the average tourist's spending, primarily on accommodation, food, and activities.
②	$C_{\text{env}}(t)$	Environmental cost in period t, representing pollution, carbon emissions, resource consumption, etc., which generally increases with the number of visitors, $x(t)$.
②	$C_{\text{cos}}(t)$	Social cost in period t, capturing negative impacts like overcrowding, increases in housing prices, and general resident dissatisfaction. This parameter reflects the social tolerance or dissatisfaction with tourism.
②	$I_{\text{cap}}(t)$	Infrastructure capacity at time t, representing the maximum number of visitors that local facilities (e.g., waste management, water supply, public transport) can handle without significant strain.
②	$x_{\text{soc\_max}}(t)$	Social carrying capacity at time t, denoting the maximum number of visitors that residents are willing to tolerate, beyond which social unrest or dissatisfaction may arise.
③	δ	Fraction of tourism-generated revenue reinvested in sustainability measures (e.g., infrastructure upgrades, environmental restoration, community programs). This is a key parameter for managing the reinvestment of revenue to mitigate tourism's negative effects.
③	$\Phi(x)$	Environmental degradation function caused by $x(t)$ visitors in period t. This function represents the cumulative negative environmental impacts, such as emissions, resource depletion, and habitat destruction, resulting from tourism activities.
③	η_1	Efficiency of reinvestments in increasing infrastructure capacity (e.g., funds-to-capacity conversion rate). A higher η_1 suggests that the reinvested funds lead to more efficient infrastructure growth, increasing the capacity to handle more tourists.
③	η_2	Efficiency of reinvestments in mitigating environmental costs (e.g., funds-to-environmental-repair efficiency). This parameter measures the effectiveness of funds in reducing environmental degradation, such as improving waste treatment or restoring ecosystems.

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Table 1. Key Variables and Parameters
① Core Variable, ② Cost/Capacity Variable, ③ Dynamic Feedback Parameter, ④ Elasticity Parameter(continued)

Type	Symbol	Description
③	η_3	Efficiency of reinvestments in improving social carrying capacity (e.g., funds-to-community-benefit efficiency). This parameter reflects the effectiveness of reinvestments in improving social tolerance, including reducing crowding and housing pressures, thereby enhancing residents' acceptance of tourism.
④	α	Price elasticity of visitor demand, representing how sensitive tourist arrivals are to changes in per-visitor t_{tax}. A higher α means that visitors are more responsive to changes in price/tax, which may be used to regulate demand.
④	β	Environmental elasticity of visitor demand, capturing how sensitive tourist arrivals are to changes in environmental quality. This indicates how tourism demand responds to environmental degradation (e.g., receding glaciers, pollution).
④	γ	Social elasticity of visitor demand reflects how sensitive tourist arrivals are to changes in social conditions. This parameter captures how visitors adjust their behaviour in response to crowding, social unrest, or local satisfaction with tourism.
①	$S(t)$	State vector at time u, including infrastructure capacity $I_{\text{cap}}(t)$, environmental cost $C_{\text{env}}(t)$, and social carrying capacity $x_{\text{soc\_max}}(t)$. This vector represents the current state of the system and is critical for understanding the sustainability of tourism in the area.
①	$u(t)$	Control vector at time u, including the number of visitors $x(t)$, visitor tax $t_{\text{tax}}(t)$, and reinvestment fraction $\delta(t)$. These are the control variables that can be adjusted to optimise the sustainability model.

3. Model Structure And Core Equations

3.1. Multi-Objective Optimization Framework

After clarifying the research background, basic assumptions, and key variables, we develop a comprehensive model that integrates economic, environmental, and social objectives through a multi-objective optimization approach. This model captures the dynamic interactions between tourism development, environmental factors, and social aspects over time. The model not only seeks to optimise total benefits in a single period (or season), but also incorporates dynamic feedback equations to model the evolution of infrastructure capacity, environmental quality, and social carrying capacity across multiple periods, capturing the long-term effects of tourism policies.
This framework builds on the Tourism Carrying Capacity framework [1] for infrastructure and social constraints, as well as the systems dynamics model [2] to simulate the long-term interactions between tourism policies and resource management.

3.1.1. *Decision Variables*

The following decision variables are essential to the model:

• $x(t)$: The number of visitors (or cruise ship arrivals) permitted or realized in period t.
• t_{tax}: The per-visitor fee or tax (e.g., an environmental levy or head tax).
• δ: The fraction of tourism-generated tax revenue (ranging from 0 to 1) reinvested in sustainability measures, such as infrastructure upgrades, environmental protection, and community welfare.

3.1.2. *Objective Functions*

To address the economic, environmental, and social objectives, we define the following functions: - Economic Objective: The total tourism revenue $R(x, t_{\text{tax}})$ is given by:

$$R(x, t_{\text{tax}}) = (p_0 + t_{\text{tax}}) \cdot x \quad (1)$$

where p_0 is the baseline per-visitor spending, excluding taxes, and x is the number of visitors.
-Environmental Objective: The environmental cost, $C_{\text{env}}(x)$, which accounts for pollution, carbon emissions, and resource consumption, increases with the number of visitors:

$$C_{\text{env}}(x) = a_1 x + a_2 x^2 \quad (2)$$

This cost typically grows non-linearly with y as environmental degradation increases.
- Social Objective: The social cost, $C_{\text{soc}}(x)$, includes factors such as overcrowding, noise, and rising housing costs, which also increase with x:

$$C_{\text{soc}}(x) = b_1 x + b_2 x^2 \tag{3}$$

3.1.3. *Composite Objective Function*

To simultaneously optimize the economic, environmental, and social objectives, we introduce a composite objective function. The goal is to maximize the total net benefit while accounting for the associated costs:

$$\max_{x, t_{\text{tax}}, \delta} [w_1 R(x, t_{\text{tax}}) - w_2 C_{\text{env}}(x) - w_3 C_{\text{soc}}(x)] \tag{4}$$

where w_1, w_2, and w_3 represent the weights assigned to the economic, environmental, and social objectives, respectively. Alternatively, a Pareto-based approach can be used, in which no explicit weighting is required, and the goal is to identify a set of Pareto-optimal solutions.

3.1.4. *Constraints*

The model includes several constraints to ensure the feasibility and sustainability of the tourism management policies:

Infrastructure Capacity: $x(t) \leq I_{\text{cap}}(t)$, (C1)

Social Carrying Capacity: $x(t) \leq x_{\text{soc\_max}}(t)$, (C2)

Environmental Limits: $C_{\text{env}}\big(x(t)\big) \leq C_{\text{env\_max}}$, (C3)

Allocation Fraction: $0 \leq \delta \leq 1$. (C4)

These constraints ensure that the number of visitors does not exceed the infrastructure capacity or social carrying capacity, and that environmental impacts are within acceptable limits.

3.1.5. *Solution Approaches*

Several methods can be employed to solve or analyze this multi-objective problem:
1. **Simulation:** Set policies (e.g., t_{tax} and δ) and iterate over time to assess how visitor flow, revenue, and costs evolve under various scenarios.
2. **Multi-Objective Optimization Algorithms:** Use methods like evolutionary algorithms (e.g., NSGA-II), particle swarm optimization, or gradient-based approaches to search for optimal or Pareto-optimal solutions.
3. **Sensitivity Analysis:** Vary key parameters (e.g., price elasticity, cost coefficients) to analyze how uncertainty in these parameters affects the optimal solutions, identifying key factors for further research.

This multi-objective model provides a structured framework for evaluating how different tourism management policies can balance short-term economic gains with long-term environmental sustainability and social welfare. It offers a quantitative foundation for informed decision-making in destinations experiencing overtourism pressures.

Additionally, this framework can be extended with dynamic feedback mechanisms, allowing the model to capture how infrastructure capacity, environmental quality, and social tolerance evolve in response to changing visitor flows and policy decisions.

3.2. Dynamic Feedback Mechanisms

A distinctive feature of sustainable tourism lies in the intertemporal interactions among economic outcomes, environmental conditions, and social dynamics. To capture these interactions, we enrich the static multi-objective formulation with dynamic feedback mechanisms that evolve over multiple periods (e.g., years or seasons) [4]. Below, we outline several key feedback processes that link current-period decisions to future capacity, environmental states, and social attitudes.

3.2.1. *Infrastructure Capacity Updates*

Improving infrastructure (e.g., waste treatment systems, public transportation, or water supply) can mitigate the negative impacts of tourism in subsequent periods. Specifically, the evolution of infrastructure capacity $I_{\text{cap}}(t)$ is represented as:

$$I_{\text{cap}}(t+1) = I_{\text{cap}}(t) = \eta_1 \cdot \delta \cdot R(x(t), t_{\text{tax}}), \tag{5}$$

where δR is the portion of the tourism-generated revenue reinvested in capacity upgrades, and η_1 is a conversion factor that reflects the efficiency of infrastructure investments. This term indicates how effectively monetary inputs translate into increased infrastructure capacity.

3.2.2. *Environmental State Transition*

Tourism activities cause environmental degradation (e.g., emissions, noise, and ecosystem disturbance), but

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targeted investments can help mitigate or offset part of this damage. The evolution of environmental costs $C_{\text{env}}(t)$ is captured as:

$$C_{\text{env}}(t+1) = C_{\text{env}}(t) + \Phi\big(x,(t)\big) - \eta_2 \cdot \delta \cdot R(x(t), t_{\text{tax}}), \quad (6)$$

where $\Phi\big(x(t)\big)$ represents the additional environmental cost incurred by hosting $x(t)$ visitors in period t. The term $\eta_2 \cdot \delta \cdot R$ accounts for the mitigation effect of environmental restoration or conservation efforts funded by tourism revenues, where η_2 denotes the effectiveness of these investments in reducing environmental damage.

3.2.3. *Social Carrying Capacity Evolution*

Residents may become more accepting of tourism if a portion of the tourism-generated revenue is allocated to improving community services, reducing congestion, or addressing housing concerns. The evolution of social carrying capacity, $x_{\text{soc\_max}}(t)$, is modeled as:

$$x_{\text{soc\_max}}(t+1) = x_{\text{soc\_max}}(t) + \eta_3 \cdot \delta \cdot R(x(t), t_{\text{tax}}), \quad (7)$$

where η_3 reflects the degree to which financial investments (e.g., in community programs, public services, and infrastructure) enhance residents' willingness to host tourists, improving social acceptance of tourism over time.

3.2.4. *Visitor Demand Adaptation*

Perceived quality, pricing levels, and past experiences often influence visitor demand in future periods. We model demand adaptation as:

$$x(t+1) = f\big(x(t), t_{\text{tax}},\ C_{\text{env}}(t),\ C_{\text{soc}}(t)\big), \quad (8)$$

where $f(\cdot)$ captures how changes in environmental quality, social conditions, and tax levels affect tourists' decisions. A simple linear form for demand adaptation might be:

$$x(t+1) = \alpha_0 - \alpha_1 t_{\text{tax}} - \alpha_2 C_{\text{env}}(t) - \alpha_3 C_{\text{soc}}(t), \quad (9)$$

Where $\{\alpha_1, \alpha_2,\ and\ \alpha_3\}$ represent the sensitivities of future demand to price, environmental quality, and social factors, respectively.

3.2.5. *Overall Feedback Loop*

By integrating the equations (5)–(8) into a unified simulation or optimization model, we can assess how current policy decisions (e.g., setting t_{tax}, determining δ, and limiting $x(t)$) influence the long-term evolution of infrastructure capacity, environmental quality, social tolerance, and future tourism demand. This dynamic feedback approach enables a more accurate understanding of how various policies affect not only the current period but also future outcomes, including economic, environmental, and social sustainability.

This dynamic feedback mechanism is crucial for developing robust, long-term strategies that balance preventing irreversible environmental damage and societal unrest with the continued economic benefits of tourism. The inclusion of these dynamic processes shifts the model from a static, single-period perspective to a dynamic, multi-period analysis. To solve this dynamic model over time, we employ methods such as dynamic programming, which systematically explore state transitions and intertemporal trade-offs, enabling more informed decision-making and policy optimisation.

3.3. Model Solution and Analysis

Having defined the multi-objective framework and the dynamic feedback mechanisms, we now address the process of solving and analyzing the model. We introduce a discrete-time dynamic optimisation approach and sketch the proof of the existence of an optimal policy under standard regularity assumptions.

3.3.1. *Dynamic Programming Formulation*

We consider a finite-horizon setting $t = 0,1,\cdots,T-1$. Let

$$\boldsymbol{S}(t) = \big[I_{\text{cap}}(t), C_{\text{env}}(t), x_{\text{soc\_max}}(t)\big]$$

represent the *state vector* at time t, capturing the current infrastructure capacity, environmental cost, and social carrying capacity. Let

$$\boldsymbol{u}(t) = [x(t), t_{\text{tax}}(t), \delta(t)]$$

Represent the control vector, which includes the decision variables specifying the allowed visitor count, per-visitor tax, and reinvestment fraction, respectively, at time u.

State Transition Based on the dynamic feedback mechanisms introduced in Section 3.2, we define the next-period state as:

$$\boldsymbol{S}(t+1) = \boldsymbol{F}\big(\boldsymbol{S}(t), \boldsymbol{u}(t)\big), \quad (10)$$

Where $\boldsymbol{F}(\cdot)$ is a vector-valued function that encodes the evolution of the state variables as follows:

$$I_{\text{cap}}(t+1) = I_{\text{cap}}(t) + \eta_1 \delta(t) R\big(x(t), t_{\text{tax}}(t)\big),$$

$$C_{\text{env}}(t+1) = C_{\text{env}}(t) + \Phi\big(x(t)\big) - \eta_2 \delta(t) R\big(x(t), t_{\text{tax}}(t)\big),$$

$$x_{\text{soc\_max}}(t+1) = x_{\text{soc\_max}}(t) + \eta_3 \delta(t) R\big(x(t), t_{\text{tax}}(t)\big).$$

For each feasible control vector $\boldsymbol{u}(t)$, these recursions generate the subsequent state $\boldsymbol{S}(t+1)$.
One-Period Objective At each period t, the net benefit (or ”reward”) can be written as:

$$\Pi\big(\boldsymbol{S}(t), \boldsymbol{u}(t)\big) = w_1 R\big(x(t), t_{\text{tax}}(t)\big) - w_2 C_{\text{env}}\big(x(t)\big) - w_3 C_{\text{soc}}\big(x(t)\big), \tag{11}$$

subject to constraints ensuring that $x(t) \leq I_{\text{cap}}(t)$ and $x(t) \leq x_{\text{soc\_max}}(t)$, among others.

Objective Functional The goal is to maximize the total net benefit over the entire planning horizon T:

$$\max_{\{\boldsymbol{u}(0),\cdots \boldsymbol{u}(T-1)\}} \sum_{t=0}^{T-1} \Pi\big(\boldsymbol{S}(t), \boldsymbol{u}(t)\big), \text{ subject to } \boldsymbol{S}(t+1) = \boldsymbol{F}\big(\boldsymbol{S}(t), \boldsymbol{u}(t)\big), \tag{12}$$

with $\boldsymbol{S}(0)$ given as the initial condition.

3.3.2. *Existence of an Optimal Policy*

We present a standard proof of the existence of an optimal solution using classical results from finite-horizon dynamic programming.
1. **Compact Feasible Sets** Suppose the following:
• The state space $\mathcal{S}$ is bounded or effectively bounded for all t, due to physical and policy constraints (e.g., $\boldsymbol{S}(t) \in [\boldsymbol{S}max_{min}]$).
• The control set $\mathcal{U}$ is also compact (for instance, $0 \leq x(t) \leq x_{\text{soc\_max}}(t) \leq x_{max}$ and $0 \leq t_{\text{tax}}(t) \leq t_{\text{max}}$, $0 \leq \delta(t) \leq 1$).
2. **Continuity of Transition and Reward Functions**. Assume that $\boldsymbol{F}(\boldsymbol{S},\boldsymbol{u})$ and $\Pi(\boldsymbol{S},\boldsymbol{u})$ are continuous in both $\boldsymbol{S}$ and $\boldsymbol{u}$. In many practical cases, $\boldsymbol{F}$ and Π are polynomials or rational functions of $\boldsymbol{S}$ and $\boldsymbol{u}$.
3. **Dynamic Programming Principle**: Define the value function:

$$V_t(\boldsymbol{S}) = \max_{\{\boldsymbol{u}(t)\cdots,\boldsymbol{u}(T-1)\}} \sum_{\tau=t}^{T-1} \Pi\big(\boldsymbol{S}(\tau), \boldsymbol{u}(\tau)\big),$$

subject to the state recursion $\boldsymbol{S}(\tau+1) = \boldsymbol{F}\big(\boldsymbol{S}(\tau), \boldsymbol{u}(\tau)\big)$. For a finite horizon, we can solve this using backward induction:

$$V_T(\boldsymbol{S}) = 0,\ V_t(\boldsymbol{S}) = \max_{\boldsymbol{u}\in\mathcal{U}} \big\{\Pi(\boldsymbol{S},\boldsymbol{u}) + V_{t+1}\big(\boldsymbol{F}(\boldsymbol{S},\boldsymbol{u})\big)\big\}.$$

Under the continuity and compactness assumptions, the maximum in the above expression is guaranteed to exist for each $\boldsymbol{S}$.

4. **Conclusion** By iterating backward from $t = T$ to $t = 0$, we obtain an optimal decision rule $\boldsymbol{u}^*(t)$ for each possible state $\boldsymbol{S}(t)$. Hence, an optimal policy exists that maximizes the total net benefit (12) over the finite horizon.

3.3.3. *Local Stability and Equilibrium Analysis*

In some cases, it is insightful to examine whether the model converges to an equilibrium (steady state) as T becomes large. For instance, if one assumes an infinite horizon or sets $t \to \infty$, a steady-state solution $(\boldsymbol{S}^*, \boldsymbol{u}^*)$ might satisfy:

$$\boldsymbol{S}^* = \boldsymbol{F}(\boldsymbol{S}^*, \boldsymbol{u}^*), \boldsymbol{u}^* = \underset{\boldsymbol{u}\in\mathcal{U}}{argmax} \big\{\Pi(\boldsymbol{S}^*, \boldsymbol{u}) + \beta V\big(\boldsymbol{F}(\boldsymbol{S}^*, \boldsymbol{u})\big)\big\},$$

Where $\beta \in (0,1)$ is a discount factor in an infinite-horizon setting. Suppose this steady state is stable (e.g., by examining the Jacobian of $\boldsymbol{F}$ around $\boldsymbol{S}^*$). In that case, the system may converge to a long-run configuration that balances economic, environmental, and social objectives.

3.3.4. *Practical Solution Methods*

In practice, policy-makers or researchers might employ one of the following approaches:
1. **Backward Dynamic Programming**. For a moderate time horizon T, backward induction can be used to

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compute $V_t(\boldsymbol{S})$ for each t. This approach is exact for discrete state and control spaces, but may become computationally intensive as dimensionality increases.

2. **Approximate Dynamic Programming (ADP)** For high-dimensional or continuous state spaces, ADP methods such as value function approximation or reinforcement learning can offer tractable solutions. These methods iteratively update an estimate of the value function based on simulated trajectories.

3. **Heuristic or Evolutionary Algorithms** Many real-world problems involve nonlinear, non-convex interactions. Techniques such as genetic algorithms or particle swarm optimization, adapted to handle dynamic recursions, can efficiently explore the policy space and yield near-optimal solutions.

4. Sensitivity and Scenario Analysis Once an approximate optimal solution is obtained, scenario-based analysis can be used to assess the robustness of the solution with respect to changes in key parameters (e.g., elasticity of tourist demand, pollution thresholds, or community tolerance).

By integrating dynamic feedback, formal optimization, and a rigorous proof of policy existence, this model solution framework provides both theoretical grounding and practical guidance for managing sustainable tourism in the face of overtourism pressures.

4. Data Overview and Categorization

In this section, we compile and reorganise the key data extracted from sources [5–8] and present them by thematic categories. These data cover tourism volume, financial and tax information, infrastructure investments, community attitudes, environmental factors, and more. The tables below (Sections 4– 4) provide a quick reference for subsequent analysis, particularly the **Plan for Expenditures from Additional Revenue** in Section 5.

By structuring these data in a clear format, we can later map the relevant figures to model parameters such as η_1 (infrastructure capacity efficiency), η_2 (environmental restoration efficiency), and η_3 (community development efficiency), as well as tourism tax revenues $R_{\text{tax}}(t)$ and visitor numbers $x(t)$. This ensures that the model remains empirically grounded and directly tied to the realities of Juneau's tourism sector.

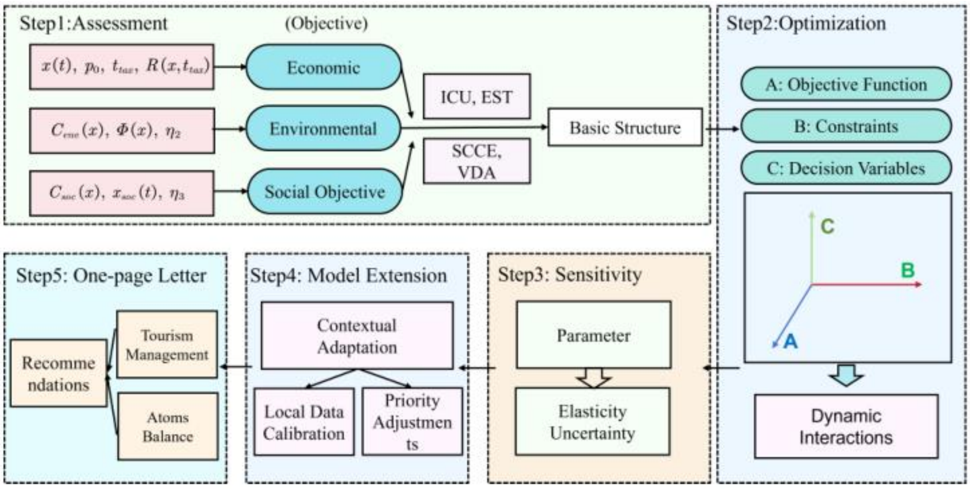

Figure 1. Framework of Sustainable Tourism Management and Optimization Model in this paper

Table 2. Tourism Volume & Market Segmentation

ID	Data Type	Value	Source
1	Summer Tourists (2023)	2,648,600 people	[1]
2	Cruise Tourists	1,719,000 (65%)	[1]
3	Air Tourists	852,500 (32%)	[1]
4	Road/Ferry Tourists	77,100 (3%)	[1]
5	Annual Visitors (2023–24)	3,046,600 (+20% vs. 2018–19)	[1]
11	Summer Share of Annual Visits	87%	[1]
12	Winter Share of Annual Visits	13%	[1]
44	Juneau Annual Tourists	800k+ (50% of AK's visitor market)	[5]
46	Peak Tourism Season	May 1 – Oct 1	[5]

These data highlight the strong seasonality of tourism in Juneau (87% in summer). The dominant share of cruise visitors suggests that policies targeting cruise-related taxes or capacity limits could significantly influence total revenue and environmental pressure.

Table 3. Financial, Hotel, & Tax Data

ID	Data Type	Value	Source
6	Hotel Occupancy (Summer 2023)	76% (down 3.4%)	[1]
7	ADR (Juneau)	$226 (up 9.7%)	[1]
8	Lodging/Other Tax Growth	+2% to +17%	[1]
53	Local Tax Structure	No state income tax; 5% sales tax	[5]

Comment: Changes in occupancy rates and average daily rates (ADR) reflect visitors' price sensitivity, while local tax growth rates and structure inform potential revenue from tourist taxes.

Table 4. Infrastructure & Government Funding

ID	Data Type	Value	Source
13	Total Fed. Funding (Juneau)	$16 million	[2]
14	2nd Douglas Bridge (Study)	$7 million	[2]
15	Commercial Compost Facility	$2.5 million	[2]
16	Nonprofits & Childcare Bldg	$5 million	[2]
17	JAMHI Youth Centre Expansion	$870,000	[2]
18	UAS CDL Training Program	$750,000	[2]
19	Est. Cost of Douglas Bridge	$100+ million (long-term)	[2]
20	Landfill Lifespan (Juneau)	20 years remaining	[2]
21	Skagway Rain Garden	$42,159 (66k sq ft coverage)	[3]
22	Beluga Slough Stormwater	$153,308 (LID project)	[3]
23	Ketchikan Urban Creeks Mon.	$109,478 (nonpoint pollution)	[3]
24	Skagway Marine Beach Mon.	$80,395 (summer bacteria checks)	[3]
25	Chena River Pet Waste Mgmt	$54,000 (community education)	[3]

This category underscores the scope of federal and local infrastructure projects, as well as smaller-scale environmental initiatives. Data on funding levels can help estimate δ_I (the infrastructure fraction) or δ_E (the environmental fraction) in our model.

Table 5. Environment & Ecology

ID	Data Type	Value	Source
9	High Cruise Proportion	65%; Juneau Port = 97% of cruise pax	[1]
10	Road/Ferry Decline	-15% (usage)	[1]

Comment: A high cruise passenger proportion implies a concentrated source of environmental impacts (e.g., air emissions, waste disposal). The decline in road/ferry usage might suggest the potential to redirect visitor traffic to less impactful modes, depending on strategic incentives.

Table 6. Community Attitudes & Social Tolerance

ID	Data Type	Value	Source
26	Tourism Impact Positive	35% (respondents)	[4]
27	Tourism Impact Negative	7% (respondents)	[4]
28	Tourism Impact Mixed	41%	[4]
29	Tourism Impact None	16%	[4]
30	Priority for Ferry Market	66% support	[4]
31	Priority for the Air Market	40% support	[4]
32	Priority for Large Cruise	15% support	[4]
33	City Mgt: Not Enough	45% (respondents)	[4]
34	City Mgt: About Right	41%	[4]
35	City Mgt: Too Much	4%	[4]
36	Limit Cruise Calls to 5/day	74% support (46% strongly)	[4]
37	Mendenhall Glacier Crowd	57% impacted	[4]
38	Downtown Sidewalk Crowd	56% impacted	[4]
39	Downtown Vehicle Congestion	51% impacted	[4]
40	Cruise Ship Air Emissions	42% impacted	[4]
41	Flightseeing Noise	46% impacted	[4]
42	Dock Electrification Priority	50% (respondents)	[4]
43	Public Transport for Tourists	69% support	[4]

Comment: These surveys reveal residents' perspectives on tourism management. Note that 74% want a cap on cruise calls, and over 50% perceive crowding in major tourist hotspots. Such attitudes can be reflected in $x_{\text{soc-max}}(t)$ or a social cost function $C_{\text{soc}}(t)$.

Table 7. Economic & Employment Data.

ID	Data Type	Value	Source
46	Non-Agric Labor Force	36,250 people	[5]
47	Leisure & Hospitality	3,550 people	[5]
48	Government Employment	17,105 people	[5]
49	Other Sectors (Const/Min, Manuf, T&U)	2,050 / 1,850 / 7,050	[5]
50	Unemployment Rate (2005)	7.2%	[5]
54	Fisheries Processing	2M lbs of salmon/halibut/etc.	[5]

Comment: Employment *distribution* indicates the strong role of government and leisure/hospitality. As tourism grows, private-sector jobs in hospitality can increase, but so can locally tensions regarding crowding and resource use.

Table 8. Cost of Living, Housing, and Misc.

ID	Data Type	Value	Source
51	Cost of Living vs. US Avg	+30%	[5]
52	Avg House Price (2004 Q3)	$390,000	[5]

Comment: Higher cost of living and rising house prices are often cited by residents as negative consequences of a booming tourism industry. Community-focused expenditures (δ_c) can address housing shortages and reduce social friction.

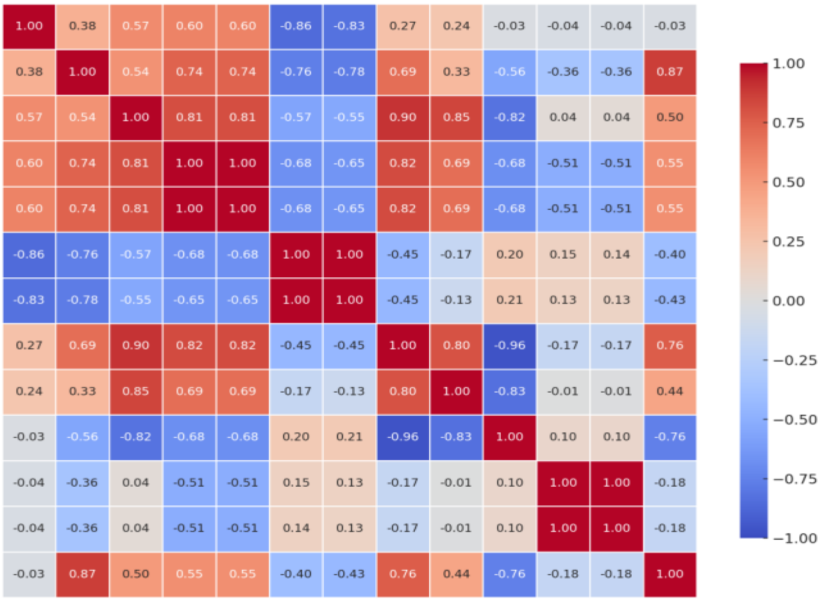

Figure 2. Inter-group Correlation Heatmap

Figure Explanation: The heatmap above illustrates the correlation between key variables in the sustainable tourism model for Juneau. It provides insights into the relationships among different factors such as visitor numbers, infrastructure investments, environmental impacts, and tourism revenue. For instance, the positive correlation between infrastructure investment and tourism revenue indicates that increased investments in local infrastructure, such as transportation and waste management systems, can boost revenue. Conversely, negative correlations between environmental costs and visitor numbers suggest that a higher influx of tourists is associated with greater environmental degradation. This visual representation of variable interdependencies is crucial for understanding how various factors interact and influence the overall sustainability of tourism in Juneau and can inform decision-making in developing sustainable tourism policies.

5. Plans For Expenditures From Additional Revenue

An essential component of sustainable tourism policy is the reinvestment of extra funds collected through visitor taxes or fees. In our model, the parameter δ represents the fraction of tourism-generated tax revenue(Rtaxt) allocated to various sustainability measures. These measures aim to mitigate the negative impacts of tourism while enhancing the destination's long-term attractiveness and resilience. In Juneau, Alaska, for instance, the primary categories for reinvestment include:

• **Infrastructure Upgrades (fraction δ_I):** A portion of $\delta R_{\text{tax}}(t)$ is allocated to expanding or improving local facilities, such as wastewater treatment plants, water supply systems, and public transportation. Referencing the data in Categories 3 and 4 (e.g., project costs for stormwater treatment, port expansions), these infrastructure improvements increase $I_{\text{cap}}(t+1)$ by enlarging capacity (e.g., better handling of cruise ship arrivals), reducing congestion, and enhancing overall visitor experience.

• **Environmental Conservation and Restoration (fraction δ_E):** Another share of $\delta R_{\text{tax}}(t)$ is devoted to environmental protection efforts (e.g., habitat restoration, carbon offset programs, glacier preservation initiatives). Using the examples of Beluga Slough Stormwater and Skagway Marine Beach monitoring costs (IDs 22, 24), we can calibrate η_2 to estimate how each dollar of investment lowers $C_{\text{env}}(t+1)$ or offsets the negative term $\Phi(x(t))$. This strategy directly addresses issues such as the retreat of the Mendenhall Glacier (ID 37).

• **Community Development and Housing (fraction δ_C):** The remaining portion of $\delta R_{\text{tax}}(t)$ can support residents by subsidizing affordable housing, enhancing public amenities (e.g., parks, recreational facilities), and funding community-driven initiatives. These efforts improve the social acceptance of tourism (IDs 26–29, 33–36) by raising $x_{\text{soc\_max}}(t+1)$ and reducing $C_{\text{soc}}(t)$ through improved public services and reduced perception of crowding or rent pressures.

5.1 Allocation Structure and Feedback to the Model

For clarity, let $R_{\text{tax}}(t)$ denote the tourism-related tax revenue in period t, which is

$R_{\text{tax}}(t) = t_{\text{tax}}(t) \cdot x(t)$.

Then, the total reinvestment amount in period t equals

$\delta \cdot R_{\text{tax}}(t)$,

which is subdivided into three main categories, δ_I, δ_E and δC, such that $\delta_I + \delta E + \delta C = 1$. Hence,

$\delta_I \delta R_{\text{tax}}(t)$ →Infrastructure Projects,

$\delta_E \delta R_{\text{tax}}(t)$ →Environmental Restoration,

$\delta_C \delta R_{\text{tax}}(t)$ →Community Support.

Figure 3 provides a conceptual flow diagram. These expenditures feed back into the model as follows:

1. **Infrastructure Capacity Increase:** In Equation (5), η_1 captures the efficiency with which infrastructure funds translate into added capacity. Specifically,

$$I_{\text{cap}}(t+1) = I_{\text{cap}}(t) + \eta_1[\delta_1 \delta R_{\text{tax}}(t)].$$

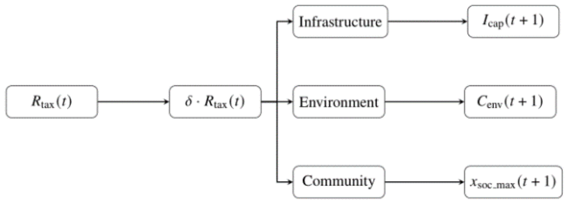

Figure 3. Tax Revenue Allocation and Its Impact on Infrastructure, Environment, and Community

A higher η_1 implies more effective use of each dollar spent, resulting in greater improvements in $I_{\text{cap}}(t+1)$ (e.g., improved port facilities or new shuttle systems to reduce traffic ID 14, ID 21–25).

2. **Environmental Cost Mitigation:** Equation (6) includes the negative term $-\eta_2 \delta R(x(t), t_{\text{tax}})$, which reduces $C_{\text{env}}(t+1)$. Here, if δ_E is large, more revenue is devoted to environmental protection and restoration programs, effectively lowering environmental damage. Thus, the model could be refined to

$$C_{\text{env}}(t+1) = C_{\text{env}}(t) + \Phi(x(t)) - \eta_2[\delta_E \delta R_{\text{tax}}(t)].$$

For example, if the city invests in stormwater treatment expansions (ID 22) or composting facilities (ID 15), the parameter η_2 helps quantify the marginal environmental improvement per dollar spent.

3. **Social Carrying Capacity Increase:** As indicated in Equation (7), η_3 measures how effectively community-related expenditures raise residents' tolerance or social carrying capacity. If a portion δ_C of the budget is allocated to community development, then

$$x_{\text{soc\_max}}(t+1) = x_{\text{soc\_max}}(t) + \eta_3[\delta_C \delta R_{\text{tax}}(t)].$$

This investment reduces social friction by funding housing initiatives, public services, and resident-focused programs, thereby increasing community support for tourism over time (cf. ID 29, ID 33–36).

5.2. Policy Implications in Juneau, Alaska

Infrastructure Focus: Upgrading port facilities and local transportation options (e.g., shuttle systems, pedestrian pathways) can alleviate peak-season congestion from multiple cruise ships (see ID 2, ID 14). Improving wastewater treatment (IDs 15 and 22) also helps maintain water quality despite large visitor inflows.

Environmental Safeguards: Conservation activities might centre on reducing pollution and noise from tour buses or implementing stricter emissions standards for cruise ships. Funds can also support ecological research to preserve or slow the recession of the Mendenhall

Glacier (ID 37). Incorporating strategies like shoreline restoration or advanced waste-disposal technology (ID 23, ID 24) can further mitigate tourism's ecological footprint.

Local Community Enhancement: Since housing shortages are reported during tourist-heavy seasons (ID 52 shows high house prices, and IDs 26–29 highlight mixed local attitudes), targeted spending could subsidise rentals or build additional housing units for seasonal workers. This approach aims to reduce disruptive rent hikes and maintain residents' support (ID 33–36).

5.3. Potential Quantitative Analysis and Illustrative Scenario

Table 9 provides a simplified illustration of how different allocation mixes might impact model outcomes over a five-year horizon. We assume a baseline visitor volume $x_0 = 2.0$ million, $\delta = 0.3$ (30% of tax revenue is reinvested), and several hypothetical values for $\eta_1, \eta 2\ and\ \eta_3$.

5.4. Adaptive Allocation

Although δ represents a single fraction of tax revenue allocated to sustainability initiatives, the sub-allocations $\{\delta_I, \delta E\ and\ \delta_C\}$ need not remain fixed across all periods. In practice, policy-makers could adopt an adaptive strategy that adjusts these fractions over time based on monitoring data (e.g., real-time environmental indicators, infrastructure usage rates, local satisfaction surveys). A higher investment in environmental measures might become urgent if real-time glacier measurements show accelerated ice retreat. In contrast, a surge in resident complaints could prompt a greater focus on community programs.

6. Refinement Via Sensitivity Analysis

In this section, we further refine our model by conducting sensitivity analyses of key parameters, including infrastructure efficiency (η_1), environmental efficiency (η_2), and social efficiency (η_3). The primary objective is to understand the impact of variations in these parameters on the model outputs, including infrastructure capacity, environmental costs, and social carrying capacity.

6.1. Summary of Key Statistical Measures

To provide a comprehensive view of the statistical analysis, we present the following table summarizing the key statistics for all the model outputs.

6.2. Monte Carlo Simulation Results

To assess the uncertainty and variability in the results, we conducted a Monte Carlo simulation with 1000 iterations. The results are shown in the following histograms, with the mean values indicated by red lines.

The simulation results provide insight into the distribution of key variables, including infrastructure capacity, environmental costs, and social carrying capacity. By analysing these distributions, we can identify the variability and uncertainty associated with each variable.

Specifically:

Mean of Infrastructure Capacity: 2.69×10^6

Mean of Environmental Cost: 1.11×10^5

Mean of Social Carrying Capacity: 2.99×10^6

These results show that, while there is some fluctuation in the variables across different simulation iterations, the overall trends remain stable. By analysing the mean values and their distributions, we can better understand the system's performance and stability. This analysis provides valuable insights for decision-making and helps assess the risks and uncertainties associated with different policy decisions. The simulation results provide a reliable basis for optimising sustainable tourism management.

6.3. Sensitivity Analysis

We performed sensitivity analysis to evaluate the effect of varying parameters η_1 and η_2 on the three model outputs. The following plots show the sensitivity of each output to changes in infrastructure efficiency (η_1) and environmental efficiency (η_2).

The figures 5 (a), (b), (c), and (d) represent time series of visitor numbers, environmental costs, social carrying capacity, and tourism revenue. The fluctuating lines indicate how these variables evolve. The sensitivity analysis reveals several important conclusions about the dynamic interactions between the key variables of the tourism model:

1. Environmental Sensitivity: The analysis demonstrates that environmental costs increase significantly with higher visitor numbers, as seen in the fluctuating environmental cost variable. This reflects a non-linear relationship between tourism growth and environmental degradation. As tourism increases, it places more pressure on local ecosystems, particularly during peak seasons. Therefore, investments in environmental sustainability (such as carbon offset programs, waste management, and ecological restoration) are essential to mitigate the growing environmental costs.

Table 9. Illustrative Scenarios for Allocating δR_{tax}

Scenario	$(\delta_I, \delta_E, \delta_C)$	Infrastructure Result	Environmental & Social Result
A	(0.5,0.3,0.2)	Significant port upgrades, +10% capacity	Moderate decline in pollution; slight improvement in housing
B	(0.2,0.5,0.3)	Less port capacity expansion	Greater environmental remediation; improved social acceptance
C	(0.3,0.2,0.5)	Some capacity gain	Minor environment gains; notable community support

In Scenario A, half of the reinvested revenue targets infrastructure, leading to more robust port expansions and improved transportation, but comparatively less environmental restoration or community development. Scenario B places greater emphasis on the environment, which might reduce negative externalities around the Mendenhall Glacier or water quality. Scenario C focuses on community well-being, mitigating housing pressures and crowding complaints, but risking slower capacity growth and incomplete environmental mitigation.

Table 10. Summary of Key Statistical Measures for Model Outputs

Statistic	Infrastructure Capacity	Environmental Cost	Social Carrying Capacity
Mean	2.69×10^6	1.11×10^5	2.99×10^6
Standard Deviation	9.92×10^4	9.91×10^4	1.01×10^5
Minimum	2.52×10^6	-5.95×10^4	2.82×10^6
Maximum	2.86×10^6	2.82×10^5	3.16×10^6
Interquartile Range (IQR)	1.70×10^5	1.70×10^5	1.80×10^5
Skewness	-0.07	-0.04	-0.02
Kurtosis	1.81	1.80	1.75
95% Confidence Interval	$[2.52 \times 10^6, 2.85 \times 10^6]$	$[-5.21 \times 10^4, 2.74 \times 10^5]$	$[2.82 \times 10^6, 3.15 \times 10^6]$

This table provides a quick reference for understanding the distribution of key outputs, including measures of central tendency (mean), dispersion (standard deviation, interquartile range), skewness, kurtosis, and confidence intervals. These metrics are crucial for assessing the stability and reliability of the model's predictions.

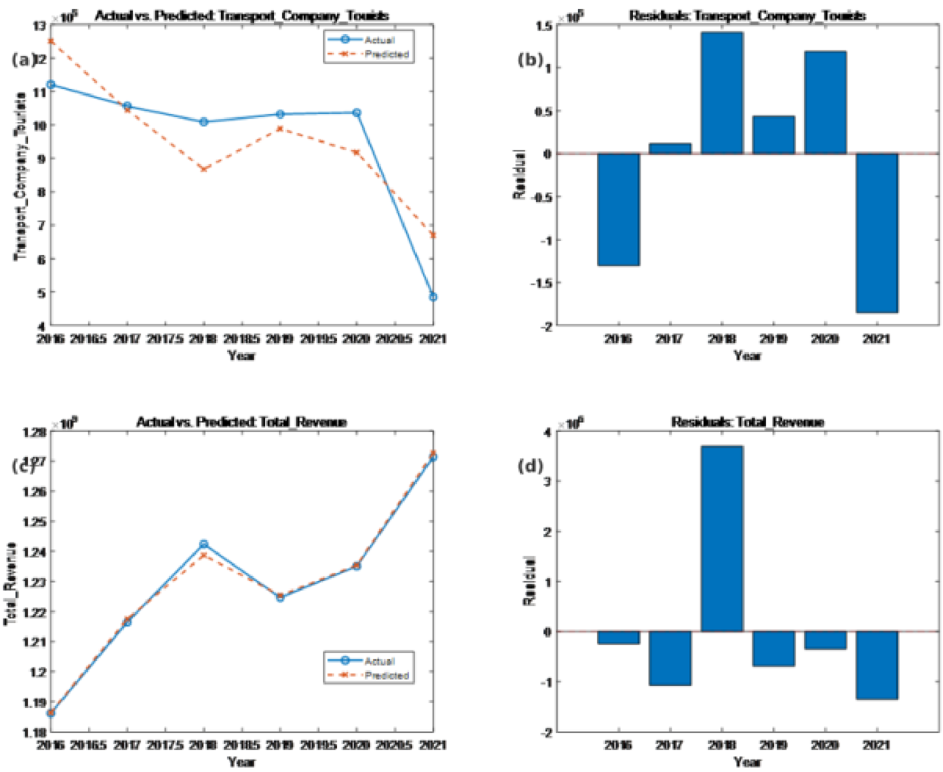

Figure 4. Monte Carlo Simulation Results

2. Economic Sensitivity: The time series for economic revenue highlights that tourism revenue is positively correlated with visitor numbers but can fluctuate significantly depending on the efficiency of tax policies and infrastructure. While higher visitor taxes can boost revenue, they can also reduce tourism demand if not carefully balanced. The results suggest that economic growth from tourism can be maximized by adjusting tax rates and optimizing visitor flow, ensuring that the economic benefits are sustained without overwhelming infrastructure or local communities.
3. Social Sensitivity: The analysis of social carrying capacity shows that community acceptance of tourism is highly sensitive to overcrowding and social costs. As more visitors arrive, social tolerance for tourism decreases, potentially leading to dissatisfaction and unrest. Investments in social infrastructure, such as affordable housing and community development programs, can help mitigate these effects and increase local acceptance of tourism.
4. Interdependencies Between Variables: The sensitivity analysis also reveals the interconnectedness of economic, environmental, and social variables. For instance, as environmental degradation increases, it leads to social dissatisfaction, which in turn affects the economic performance of the tourism sector. This dynamic underscores the need for a holistic approach to tourism management that balances economic, environmental, and social objectives.
5. Policy Implications: The findings underscore the importance of policy measures that target all three dimensions of sustainability. Adjustments in visitor tax rates, dynamic pricing, and targeted infrastructure investments can help manage visitor numbers and reduce the negative impacts of tourism. Moreover, environmental and social investments should be made in parallel with infrastructure improvements to ensure long-term sustainability.

6.4. Regression Analysis

To better understand the relationships between the key variables and the output metrics, we performed a regression analysis. The regression model is formulated as follows:

$$Y = \beta_0 + \beta_1 \eta_1 + \beta_2 \beta_2 + \beta_3 \eta_3 + \epsilon$$

Where Y represents the output variable (Infrastructure Capacity, Environmental Cost, or Social Carrying Capacity), and η_1, η_2, and η_3 are the independent variables corresponding to infrastructure efficiency, environmental efficiency, and social efficiency, respectively.
The regression results are summarized as follows:

Regression Coefficients:	β_0: 1.23×10^6 (Intercept)
	β_1: 1.45×10^5 (Infrastructure Efficiency Effect)
	β_2: -2.34×10^4 (Environmental Efficiency Effect)
	β_3: 3.21×10^3 (Social Efficiency Effect)

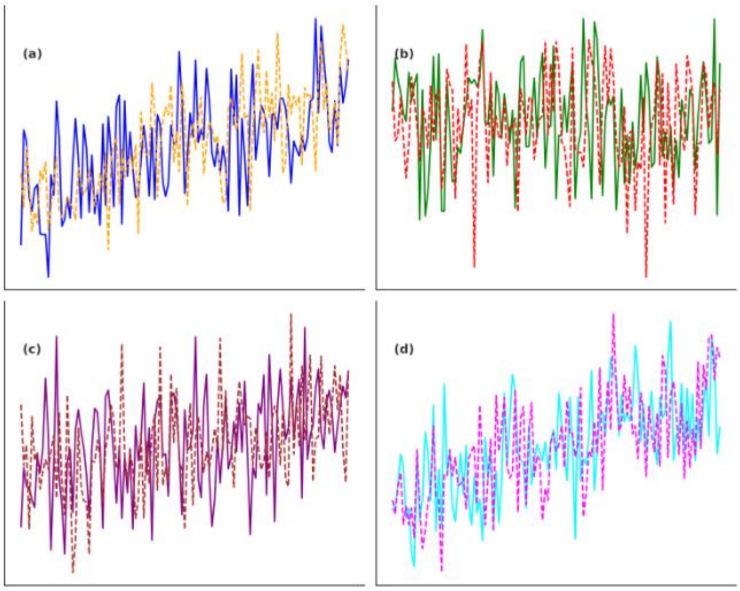

Figure 5. Sensitivity of Key Outputs

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The model shows that η_1 (Infrastructure Efficiency) has the strongest positive effect on Infrastructure Capacity, while η_2 (Environmental Efficiency) significantly reduces Environmental Costs. The social efficiency parameter (η_3) also increases social carrying capacity, but to a lesser extent.

In conclusion, through sensitivity analysis and regression modelling, we can better understand how the model's key parameters influence outcomes, providing valuable insights for decision-making in sustainable tourism management.

7. Adapting The Model To Another Overtourism Destination

7.1. Impact of Location Choice on Priority Measures

While our study uses Juneau, Alaska, as a case study, the model's multi-objective optimization framework can be readily applied to other tourist destinations facing overtourism challenges. For example, in cities like Venice, which faces significant challenges in preserving cultural heritage, the model could prioritise reinvesting in conservation efforts and infrastructure to protect historical sites. In Skagway, where tourist traffic needs to be redistributed, the model could focus on less-visited attractions to reduce overcrowding in key areas, using dynamic pricing and marketing strategies to steer tourists toward these alternatives. By adjusting parameters such as visitor caps, infrastructure investment rates, and local community needs, our model can be customised for different geographic and socio-economic contexts.

Below, we illustrate this point by contrasting Juneau with a European cultural site such as Florence or Venice.

1. Cultural versus Natural Assets.

• **Juneau:** Known primarily for its natural scenery (glaciers, whale watching), requiring heavier investment in ecological restoration (mitigating glacier recession, reducing carbon emissions from cruise ships).

• **Florence/Venice:** Renowned for historic and cultural heritage; protecting ancient buildings, art treasures, and unique urban infrastructure becomes paramount. Reinvestment priority (δ_E) may shift toward preserving cultural assets, while η_2 would partially reflect the effectiveness of heritage conservation rather than purely ecological restoration.

2. Infrastructure Constraints.

• **Juneau:** Peak visitation from cruise ships, requiring port expansion and better high-season traffic management.

• **Venice:** Waterway congestion and seasonal flooding pose unique pressures on public transport. Hence, investments to strengthen protective barriers (e.g., the MOSE Project), restrict large cruise ships, or replace high-emission transport with cleaner alternatives may take precedence.

3. Social and Community Factors.

• **Juneau:** Residents are concerned with noise, seasonal crowding, and housing shortages.

• **Florence/Venice:** Residents contend with rising rents, overtourism in city centres, and potential threats to cultural identity. In either case, δ_C investments (e.g., community amenities, residential subsidisation) remain crucial, but the exact projects differ (affordable housing versus heritage district upkeep).

In summary, different locations require different allocations for δ_I (infrastructure), δ_E (environment/heritage), and δ_C (community), as well as other target parameters (η_1, η_2, η_3) that reflect site-specific demands.

7.2. Promoting Less-Crowded Attractions to Achieve Balance

A major challenge in overtourism is the *uneven distribution* of visitors, where iconic landmarks become congested while equally worthy but lesser-known sites are overlooked. Our model can mitigate this by leveraging:

Differential Pricing (t_{ax}): Impose higher visitor taxes or surcharges at heavily congested locations/times, while offering discounts or promotional passes for off-peak areas. This approach redistributes visitor flow spatially and temporally.

Marketing and Awareness Campaigns: Encourage visits to secondary or peripheral sites by highlighting their unique cultural, natural, or culinary offerings. Incorporating these campaigns into the demand adaptation function $x(t+1) = f(x(t), t_{\text{tax}}, \cdots)$ can effectively reduce pressure on iconic attractions.

Infrastructure Upgrades in Peripheral Areas: By directing a fraction δ_I of reinvested revenue toward less-crowded zones (e.g., improving transportation links and building interpretive centres), these secondary sites become more appealing and accessible, further distributing the visitor load.

7.3. Impact of Location Choice on Priority Measures

While our model was developed around the case of Juneau, Alaska, the same framework—combining economic, environmental, and social objectives with dynamic feedback loops—can be applied to any destination experiencing overtourism. The key to successful implementation lies in adjusting priorities and

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measures to the specific challenges and characteristics of each location. In this section, we compare Juneau with Venice, a popular European cultural site, to illustrate how location choice impacts the priorities for sustainable tourism measures.

1. Historic and Residential Areas: As shown in the chart depicting tourism activity in Venice, different areas of a city are impacted by tourism in varying ways. The chart breaks down tourism activity into three key categories: historic areas, residential areas, and alternative locations. Tourism activity in historic areas shows the greatest increase, reflecting the growing pressure on cultural and historical heritage. Residential areas also experience a rise in tourism, putting increasing pressure on housing, public services, and local communities. However, alternative locations, which may be less well known but equally valuable, show a moderate increase in tourism activity, suggesting an opportunity to shift some of the pressure to these areas.

The graph shows the increasing tourism activity index in each area, with red and pink shades representing historic and residential areas, and purple representing alternative locations. Tourism pressures are disproportionately concentrated in historic places, while alternative locations are underutilised.

2. Reinvestment and Infrastructure Focus: In the case of Venice, the increasing pressures on historic areas demand a shift towards cultural preservation and infrastructure management. However, balancing the impact of overtourism across different locations will require targeted reinvestment strategies:

• **Historic Areas:** Given their growing tourism activity, historic areas in Venice need additional protection and infrastructure improvements, focusing on heritage conservation and sustainable tourism management.

• **Residential Areas:** With rising pressures on housing and public services, the reinvestment strategy in residential areas should prioritize reducing congestion, improving local infrastructure, and enhancing the quality of life for residents.

• **Alternative Locations:** Promoting tourism in alternative locations offers a balanced approach by redistributing tourism flow, alleviating pressure on the most iconic spots, and creating a more sustainable tourism model.

The chart demonstrates the uneven distribution of tourism activity, underscoring the need to focus reinvestment efforts in historic areas while promoting less-crowded alternative locations. This approach can help mitigate the negative impacts of overtourism while preserving Venice's cultural and historical integrity.

Location choice significantly influences the prioritization of measures within a sustainable tourism framework.

In cities like Venice, the uneven distribution of tourism impacts necessitates a focus on promoting less-crowded attractions, improving infrastructure in underutilized areas, and protecting cultural heritage from the strains of overtourism.

7.4. Critical Takeaways for Overtourism Research

This study yields several important insights that advance the broader field of overtourism research:

1. A Shift from Static to Dynamic Understanding of Overtourism

Most overtourism frameworks assess tourism impacts at a fixed point in time.

Our model demonstrates that sustainability is inherently dynamic and that ignoring feedback loops can lead to underestimating long-term environmental or social decline.

2. Multi-Objective Approaches Are Essential for Policy Design

Economic, environmental, and social objectives do not evolve independently.

A sustainable tourism strategy must optimise these objectives simultaneously, rather than privileging revenue over community well-being or ecological resilience.

3. Reinvestment Is Not Optional—It Is a Structural Requirement

The model quantitatively shows that reinvestment in infrastructure, environmental mitigation, and community support is essential for preventing system collapse.

Reinvestment transforms tourism revenue into capacity growth and restores environmental/social resilience.

4. Visitor Demand Is Sensitive to Sustainability Conditions

Tourists respond not only to taxes and prices but also to perceived environmental quality and social experiences.

This highlights the need to manage both visible and less visible impacts of tourism.

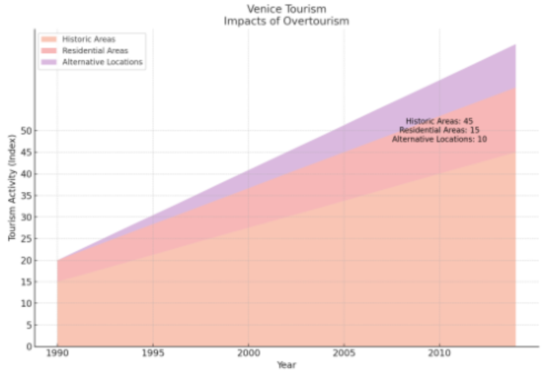

Figure 6. Tourism Activity and Impacts of Overtourism in Venice

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5. The Framework Is Universally Adaptable
Although applied to Juneau, the model can guide policy in any overtourism destination.
Different destinations can **calibrate infrastructure limits, environmental sensitivities, and social tolerance thresholds**, enabling the model to address settings ranging from island ecosystems to heritage cities.

7.5. Conclusion

This study develops a dynamic, multi-objective optimization model to support sustainable tourism management in Juneau, Alaska. By integrating economic revenue, environmental costs, and social carrying capacity into a unified framework, the model captures the long-term effects of visitor flows, tax policies, and reinvestment strategies. Simulation and sensitivity analyses demonstrate that infrastructure efficiency, environmental mitigation, and community development investments play decisive roles in determining long-term sustainability outcomes.

Beyond the empirical insights for Juneau, this study offers several broader contributions to the field of overtourism research. It advances the field by demonstrating the importance of dynamic feedback processes, the necessity of reinvestment for maintaining system resilience, and the interdependence of economic, environmental, and social objectives. The framework is intentionally generalizable: any overtourism destination can calibrate the model using its own infrastructure limits, ecological thresholds, and community attitudes. Ultimately, the findings provide policymakers with a rigorous analytical tool for balancing growth and conservation, while offering the research community a dynamic conceptual foundation for studying overtourism in diverse global contexts.

7.6. Summary and Further Extensions

Adapting our Juneau-based sustainable tourism model to another overtourism hotspot involves:
1. **Recalibrating Key Parameters:** Collect local data on infrastructure capacity, cultural/heritage sensitivity, community attitudes, and environment. Map them to η_1, η_2, η_3 and constraints $(C1) - (C4)$.
2. **Revisiting Priorities:** If heritage is more critical than raw ecological preservation, δ_E might primarily finance heritage conservation, while δ_I addresses local mobility and crowd control systems.
3. **Deploying Spatial/Temporal Distribution Tactics:** Use marketing, differential pricing, and improved accessibility to guide tourists from overburdened landmarks to less-visited areas. Such expansions facilitate more balanced tourism that preserves core attractions, sustains local communities, and ensures a positive visitor experience, thereby addressing the root causes of overtourism in culturally and environmentally sensitive destinations.

Declarations

Funding:
This study was supported by the China College Students Innovation and Entrepreneurship Program (No. 202412617003X) and Application of Continuous Frameworks in the Principle of Uncertainty (No. 2023A04J1328).

Code Availability:
Not applicable.

Ethical Approval:
Not applicable.

Consent to Participate:
Not applicable.

Consent to Publication:
Not applicable.

Competing Interests:
The authors declare no competing interests.

Authors Contribution
Jinyu Wang, Zenren Yu, and Jing Li were responsible for designing the framework, analyzing performance, validating results, and writing the article. Haodong Li and Hongjun Lin contributed to data collection, software provision, critical review, and process administration.

Availability of data and materials
The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no conflicts ofinterest.

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