Multi-objective optimization based on dynamic planning for sustainable tourism modeling

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Abstract. In recent years, many areas such as Juneau, Alaska, USA have been affected by over-tourism, which has led to ecological degradation and affected the normal life of residents. This study aims to build a sustainable tourism model, to balance economic and ecological sustainable development, and solve the problem of tourism overdevelopment. This paper researches a business system that balances economic growth and ecological health by building a multi-objective optimization sustainable tourism model based on dynamic planning. To establish a sustainable tourism model, this study takes Juneau as the research object, selects five objective functions and influencing factors, collects data on the number of tourists, annual income, and CO_2 annual emissions in Juneau, to establish the objective equations with constraints. This paper normalizes the data, sets up a dynamic weight adjustment mechanism to assign weights, and uses MATLAB to get the optimal annual results in the five aspects, and visualizes the results. Finally, a sensitivity analysis of the model is performed, and the results show that the number of tourists is the core factor affecting sustainable tourism. Based on this, this paper proposes a revenue expenditure strategy of spending 30% of the additional revenue on infrastructure development and 50% of the additional revenue on environmental protection. The study shows that the model has feasibility and practical significance, and it can effectively analyze the influencing factors of sustainable tourism, provide a basis for tourism development, and is of great significance to sustainable tourism development.

Keywords: Multi-objective optimization, Dynamic programming, Sensitivity analysis, Sustainable tourism, Data standardization.

1. Introduction

1.1. Background

With the booming of tourism, the problem of overdevelopment of tourism has become more and more prominent. Take Juneau in the United States as an example, the influx of tourists has brought economic benefits, but it has also caused many negative impacts: the influx of tourists has led to an increase in the pressure on the infrastructure, the lives of residents have been interfered with (as in figure 1), while rising temperatures have caused the glaciers to recede, and the ecological environment is facing a huge challenge. Without proper planning, Juneau's tourism industry will not be sustainable. In addition, this phenomenon of over-exploitation is widespread around the world, with huge impacts on the economy and social environment, so it is urgent to construct a sustainable tourism model.

To meet the urgent need to build sustainable tourism, governments and other sectors have taken measures to increase tax rates and implement green tax systems to meet the “double carbon” goal, and further use tax revenues for the construction of infrastructure to improve the level of resource conservation and intensive utilization [1]. Therefore, this study builds a sustainable tourism model for the city of Juneau, Alaska, to balance economic income, sustainable development of natural resources, and the interests of residents. In the process of modeling, this paper considers factors such as the number of tourists, overall income, etc., studies these influencing factors through relevant data, and provides revenue expenditure strategy based on the results of the study. Finally, sensitivity analysis is carried out to determine the most influential factors, to make a comprehensive plan for the development of sustainable tourism.

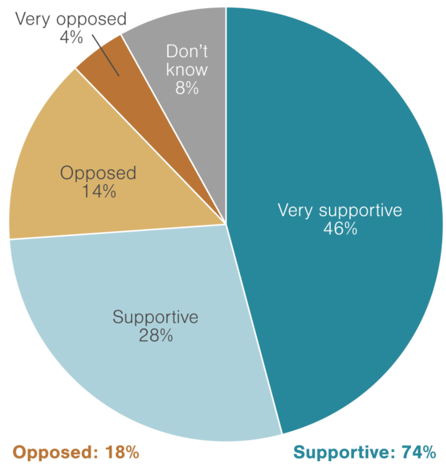

Figure 1. Background survey about residents' view of limiting the number of large cruise ships in Juneau's harbor

1.2. Literature review

Previous studies have explored sustainable tourism in places such as the City of Juneau with some success. The Department of Landscape Architecture in the College of Design at North Carolina State University has worked with the City of Juneau and the Southeast Alaska Department of Public Administration to use the Map Factory system to study tourism development and resource utilization in Juneau in an attempt to map out the future direction of the city. The University of Washington [2] broke with the linear approach and built on the work of designers to explore community benefits of municipal solid waste in Juneau, ultimately envisioning a waste-to-energy "mini-material park". Zhao Jie [3] explains the concept of sustainable tourism through the discussion of over-tourism, and puts forward the development strategy of sustainable tourism at the theoretical level from the perspectives of government, enterprises, and the public. Zijin College of Nanjing University of Science and Technology [4] conducted a study on the "emission reduction effect and mechanism of carbon tax and carbon trading" and analyzed the necessity and feasibility of introducing a carbon tax. The School of Economics and Management of Tarim University [5] took Shuimogou Village in Mubi Kazakh Autonomous County of Xinjiang as the research object, utilized the research methods of literature research, questionnaire survey and field interview, and put forward the countermeasures for the synergistic development of the traditional villages' protection and sustainable tourism by using entropy value calculation method.

Previous scholars have introduced different perspectives on the interpretation of the connotation of the concept of over-tourism, which is broadly categorized into the social carrying capacity, quality of life, and comprehensive perspective. From the existing literature, most of the past research stays at the theoretical level, with case-based empirical evidence as the mainstream research method, mainly qualitative research, and does not give specific actionable programs and measures [6]; or is limited to a small range of areas, and is not the result of the calculation of the universal model. Therefore, this study aims to construct a sustainable tourism model applicable to Juneau City with universal applicability, comprehensively consider the balance between economic benefits and the interests of residents, through the collection of data, study the factors affecting sustainable tourism, clarify the optimization objectives and constraints and establish a model, thus providing an innovative approach to solving the problem of over-tourism.

2. Preparation and model method

2.1. Data overview

2.1.1 Data collection

This study compiles data on the number of visitors to Juneau over time, the annual income of residents, and CO_2 emissions by collecting information such as the Juneau Tourism Board's annual financial reports.

Due to the large amount of data and the complexity of the order of magnitude, it's not convenient to list them all, this paper will do the normalization and visualization of the important data.

2.1.2 Data Screening

This paper collected essential data from the official website, and other useful data sources are shown in Table 1.

Table 1. Data and Database Websites

Region	Database Names	Database Websites
Juneau	Visitor volume	https://www.alaskatia.org/resources/research
	Tourist rate	https://juneau.org/finance/controller

2.1.3 Data standardization & Visualization

By retrieving information from the Juneau Municipal Government's annual financial report and the number of tourists in the Tourism Bureau, it was found that the order of magnitude of the variables varied greatly, and to avoid numerical overflow or other instability in the objective function, this paper standardizes the data collected. In this paper, the normalization method of standardization is used to normalize the data to obtain the results of the standardized data scaled to [0,1], and the formulas used are as follows.

$$x_{norm} = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{1}$$

Where x_{norm} denotes the normalized variable.

After statistically analyzing and normalizing the collected data, the main data were visualized using grouped bar charts, and stacked bar charts as shown in Figure 2.

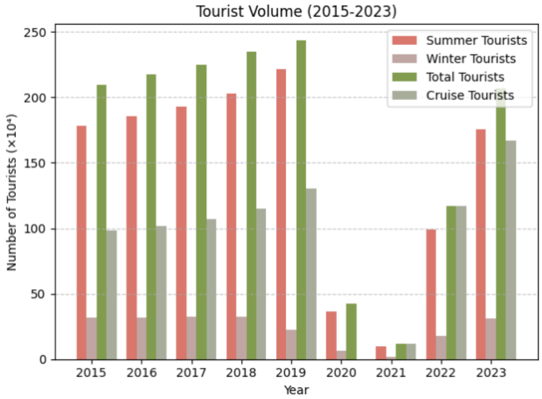

Figure 2. Juneau tourist volume

Note: Due to COVID-19, Data for 2020-2022 are specially treated based on the assumption: based on historical statistics, it is assumed that summer visitors make up 85% of the year.

2.2. Model method

This study establishes a sustainable tourism model and analyzes the influencing factors, this paper mainly uses the method of dynamic multi-objective optimization [7] and establishes relevant constraints to realize the model. In this paper, five objective functions are set by analyzing the research objectives: maximizing tourism revenue, minimizing environmental impacts, maximizing resident satisfaction, minimizing congestion, and maximizing resident income contribution. Considering Juneau's influencing factors for sustainable tourism development, and taking into account that additional tourist taxes may increase local government revenues, among other reasons, this paper summarizes them into five main research factors: the number of tourists, the rate of tourist taxes, carbon dioxide emissions, residents' income, and the size of the labor force. Then, according to the preference of the decision maker, the dynamic weights are assigned to each objective function with full consideration of different situations, such as environmental protection priority or fiscal revenue priority, etc. This paper transforms the multi-objective optimization problem into a single-objective optimization problem by flexibly adjusting the weights and introducing the time dimension.

3. Establishment and Solving of Sustainable Development Model

3.1. Preparation of the model

3.1.1 Optimizing factors and Main constraints

In the model of sustainable tourism constructed in this paper, the factors that are optimized and those that are used as constraints are shown in Table 2.

Table 2. Optimizing factors and Main constraints

Optimizing factors	Main constraints
Maximize tourism revenue(economics)	The number of visitors
Minimize environmental impact(environment)	Tourist rate
Maximize resident satisfaction(society)	Carbon dioxide emissions
Minimize congestion(society)	Resident income
Maximize the contribution of residents' income(society)	Workforce size

3.1.2 Research process

The flow of this study is shown in Figure 3.

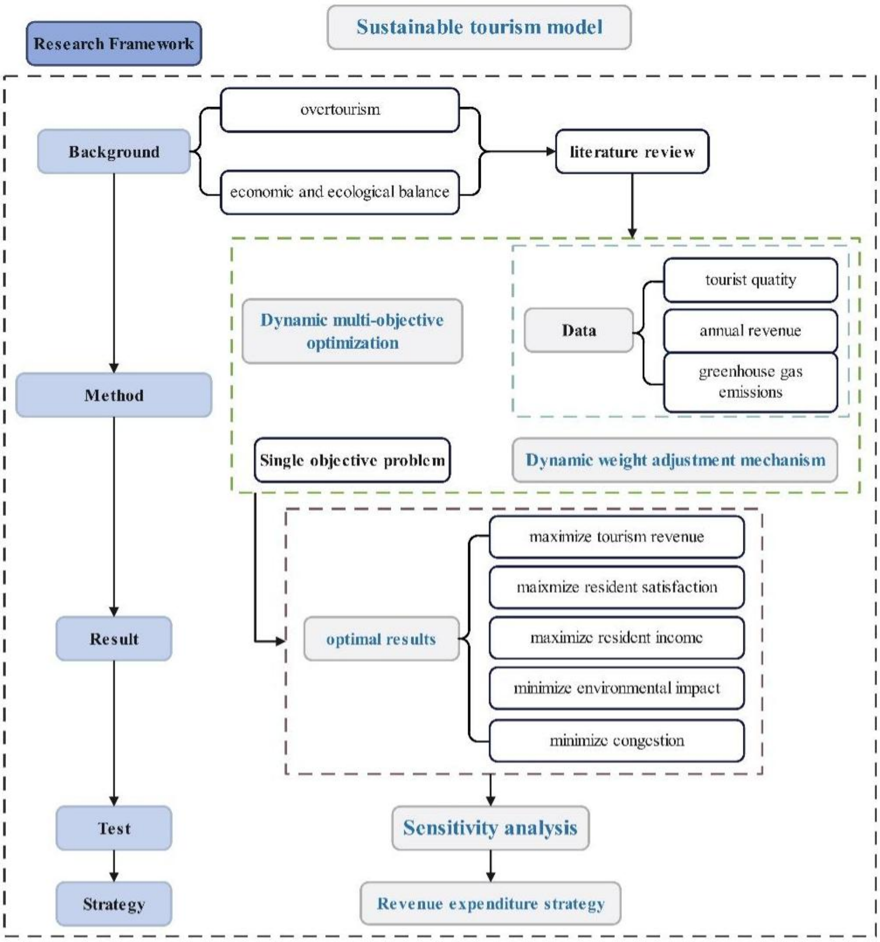

Figure 3. Study flow chart

3.2. Establishment of Sustainable Tourism Development Model

Based on the data from the annual financial reports, this paper selects five main factors that influence the development of sustainable tourism: tourism revenue, environmental impact, residents' satisfaction, urban congestion and residents' personal income. The weights are set for different parameters: w_1 for tourism income, w_2 for environmental impact, w_3 for residents' satisfaction, w_4 for congestion, and w_5 for residents' personal income.

3.2.1 Multi-objective optimization

The problem of studying the optimization of more than one objective function over a given region is known as a multi-objective planning problem and is usually notated as, MOP (multi-objective-programming). Among them, the linear weighting method [8] is widely used in multi-objective optimization, which represents the problem with multiple objectives in mathematical language in the following form by linearly weighting multiple optimization objectives by weights set according to their importance.

$$y = min \sum_{k=1}^{K} \lambda_k f_k(x)$$

$$s.t. \begin{cases} g_i \geq 0, i \in [1.M] \\ h_j(x) = 0, j \in [1, L] \end{cases} \tag{2}$$

Where $g_i \geq 0, i \in [1, M]$ defines the inequality constraints that the decision variable x must satisfy, and $h_j(x) = 0, j \in [1, L]$ denotes the equation constraints that the decision variable x must satisfy. By setting these constraints as preconditions in the model, the sustainability of the model is enabled. Moreover, converting the multi-objective planning problem into a single-objective optimization problem is more convenient for research, so this method is used to build the model in this paper.

3.2.2 Dynamic weight adjustment mechanism

The dynamic weight adjustment mechanism [9] is an optimization mechanism for the dynamic planning algorithm: according to the importance and similarity of the features of each part of the time series, the corresponding weights of the matching points are dynamically adjusted. This mechanism can not only reduce the interference of non-key features on the results, but also enhance the matching influence of key feature factors, so as to more accurately reflect the degree of influence of each factor on the results.

In this paper, the sustainable tourism model is constructed by assigning dynamic weights to each objective function, thus transforming it into a univariate problem. Further, the dynamic weight adjustment mechanism is used to construct an optimization model suitable for long-term management by flexibly adjusting the dynamic weights as shown below.

At each time step t, the weights are dynamically adjusted according to the following rules:

(1)If $E(t) > (CO_2)_{max}$, environmental impact weight (w_2) increases;

(2)If $R(t) < R_{min}$, income weight (w_1) increases;

(3)If $L(t) < L_{min}$, residents' satisfaction weight (w_3) increases.

where E(t) denotes environmental impact, R(t) denotes tourism revenue, L(t) denotes resident satisfaction, and CO_2(t) denotes carbon dioxide emissions.

Adjusted to normalize all weights:

$$w_i = \frac{w_i}{\sum w_i} \tag{3}$$

Where w_i denotes the weight of each factor.

3.2.3 Objective function and constraints

Based on the above methods and information, this paper finally optimizes the following multi-objective weighted summation function:

$$F = w_1 \cdot R(t) - w_2 \cdot E(t) + w_3 \cdot L(t) - w_4 \cdot C(t) + w_5 \cdot R_{income}(t) \tag{4}$$

Where w_1 is a weight on tourism income, w_2 is a weight on environmental impact, w_3 is a weight on resident satisfaction, w_4 is a weight on congestion, and w_5 is a weight on residents' personal income.

Of these, the relevant variables are shown in Table 3.

Table 3. Variables and expressions

Variables	Expression
Tourism revenue R(t)	$R(t) = N(t) \cdot (100 - 100 \cdot T(t))$
Environmental impact E(t)	$E(t) = 0.02 \cdot N(t) + 0.01 \cdot I(t)$
Resident satisfaction L(t)	$L(t) = \frac{P(t)}{N(t)} - 0.1 \cdot T(t)$
Degree of congestion C(t)	$C(t) = \frac{N(t)}{N_{max}}$
contribution of residents' income $\boldsymbol{R_{income}(t)}$	$R_{income}(t) = 0.5 \cdot N(t) \cdot Labor(t)$

Where N(t) denotes the number of visitors, T(t) denotes the tourist rate, I(t) denotes infrastructure investment, and Labor(t) denotes the size of labor force.

The constraints of this objective function, taking into account the influences of sustainable tourism, are shown below:

The total budget constraint is $I(t) + P(t) \leq Budget$.

The CO_2 emission constraint is $CO_2(t) = 0.02 \cdot N(t) + 0.01 \cdot I(t) \leq CO_{max}$.
The size of labor force is $Labor(t) \geq Labor_{min}$.

3.2.4 Model solving

Based on the initial judgment, this paper considers that all the influencing factors of sustainable tourism programs have the largest proportion of tourism income and the smallest proportion of congestion. Then initialize the weights and set their weights as $w_1 = 0.3$ for tourism income,$w_2 = 0.2$ for environmental impacts, $w_3 = 0.2$ for residents' satisfaction,$w_4 = 0.1$ for crowding degree, and $w_5 = 0.2$ for residents' personal income, respectively, as shown in Figure 4.

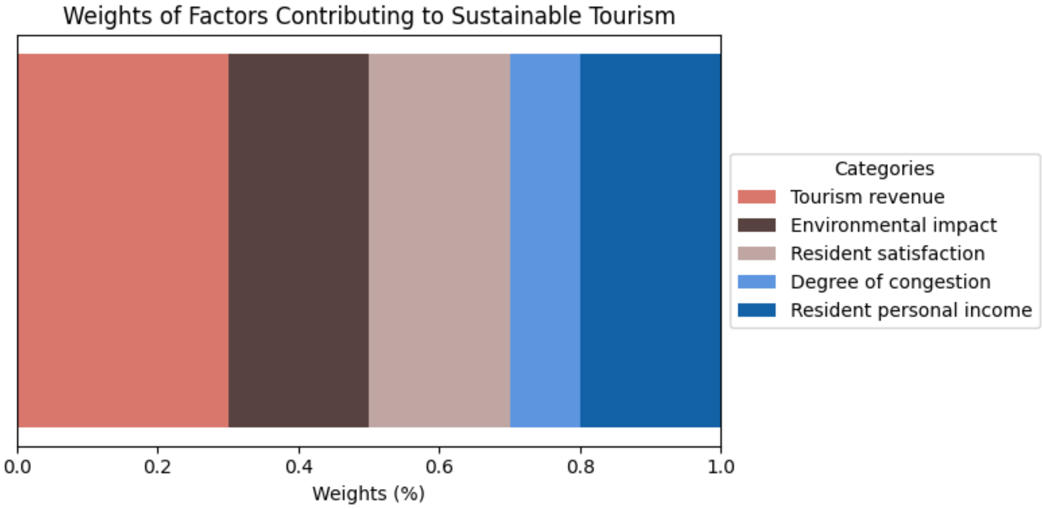

Figure 4. Weights of factors

According to the reasonableness assumption: Based on the biological knowledge, it is assumed that the CO_2 emission is abiotic CO_2 emission, which ultimately yields the maximum value of CO_2 emission as 0.8, the minimum value of labor force size as 0.5, and the budget as 1. Thus, the study obtains the optimal results for the year as shown in Table 4.

Table 4. Best results of the year

Years	Infrastructure investment	Resident input	Overall target value	CO_2 emissions	Resident income
2011	1.25e-05	0.99999	2e+05	1.25e-07	0
2012	4.6088e-08	1	3.1773	0.0012291	0.023036
2013	5.0368e-08	1	0.28348	0.0067389	0.079562
2014	4.3244e-08	1	0.44719	0.0057829	0.044211
2015	9.5403e-08	1	-0.20901	0.012804	0
2016	1.2275e-07	1	-0.36524	0.016506	0.13471
2017	1.4847e-07	1	-0.45716	0.02	0.23419

The annual changes in infrastructure investment and resident inputs are shown in Figure 5(left), the sum of which does not exceed the total budget of the Juneau Municipality as well as the Tourism Authority. The total target value is shown in Figure 5(right).

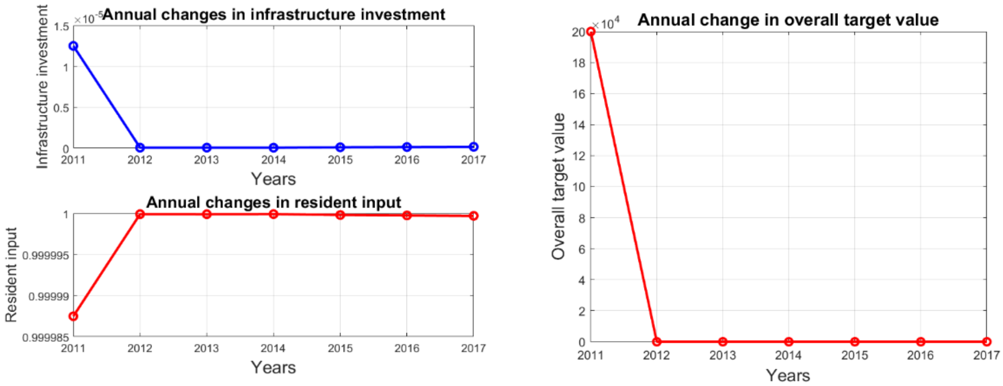

Figure 5. Annual changes in infrastructure investment and residents' investment(left) and Annual change in overall target value(right)

CO_2 emissions are shown in Figure 6(left). The personal income of the population is shown in Figure 6(right).

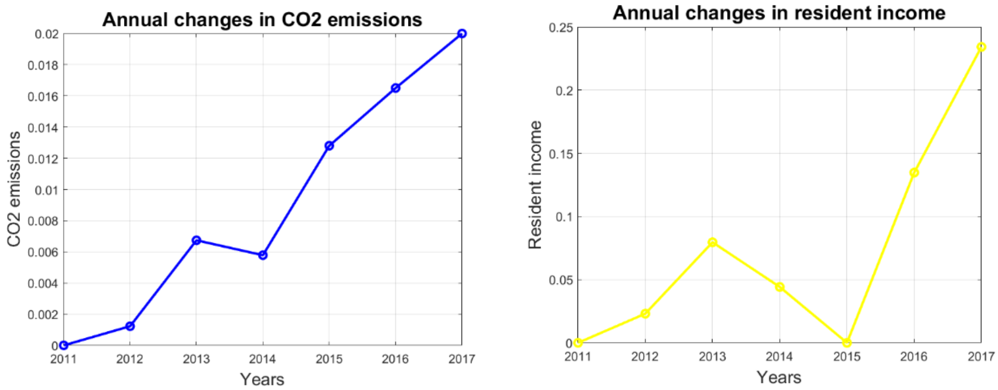

Figure 6. Annual changes in CO2 emissions(left) and Annual changes in household income(right)

3.3. Sensitivity Analysis of Model

Sensitivity analysis [10] is a method to study and analyze the sensitivity of a system or model's state or output changes to changes in system parameters or surrounding conditions. Sensitivity analysis is often used in optimization methods to study the stability of the optimal solution when the original data are inaccurate or changed, and sensitivity analysis can also determine which parameters have a greater impact on the system or model, so this paper uses sensitivity analysis to test the established model. Therefore, this paper uses sensitivity analysis to test the established model.

There are generally two main approaches to sensitivity analysis:

(1) Changing parameter values directly to assess the change in outcome;

(2) Varying the parameter values to assess the change in the dependent variable concerning the independent variable.

In this study, sensitivity analysis is carried out to assess the effect of different factors on the objective function. Therefore, to find the required optimal value, the first method is used.

The main purpose of sensitivity analysis is to identify the most important driving factors by adjusting the key parameters in the model one by one and observing the extent to which these changes affect the target values. In the process of model building, the study chooses the following five parameters as the main objects of sensitivity analysis: the number of tourists, tourist tax rate, carbon dioxide emissions, residents' income, and labor force size. To ensure the scientificity and stability of the analysis, this paper adjusts the value of each parameter by ±50% based on its historical data, while other parameters remain unchanged. Among them, in the adjustment process, to avoid the calculation problems caused by too small values, this paper restricts the minimum value of all parameters to non-zero values.

In this case, each parameter is individually adjusted by ±50% and the absolute value of the difference between the target values before and after the adjustment is calculated as a sensitivity indicator, as follows:

a. Select a single parameter for adjustment;

b. Fix the other parameters;

c. Solve the adjusted target value by the optimizer;

d. Calculate the absolute difference between the target values before and after adjustment and use it as a sensitivity indicator.

By writing and running the MATLAB code, the final results of the sensitivity analysis for the number of tourists, tourist tax, CO_2 emission, residents' income and workforce size are shown in Figure 7:

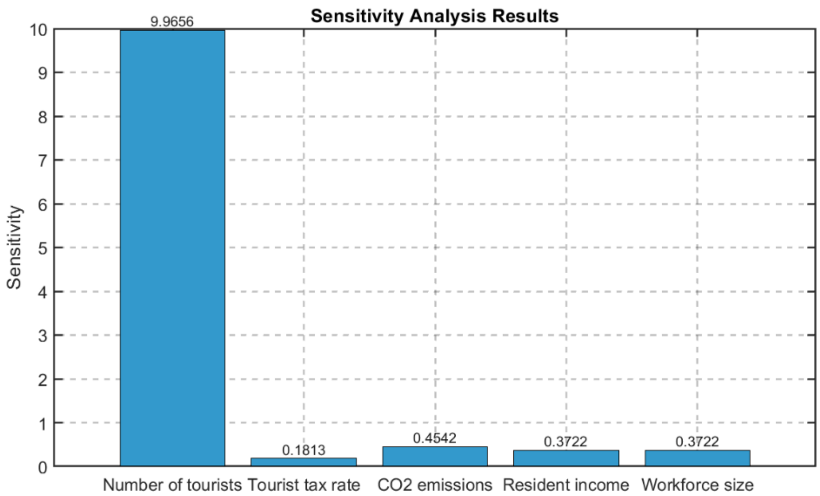

Figure 7. Sensitivity of parameters affecting tourism in Juneau

Fill in the table with the results of the MATLAB run as shown in Table 5.

Table 5. Sensitivity of parameters affecting tourism in Juneau

Parameter	Sensitivity
Number of tourists	9.9656
Tourist tax rate	0.1813
CO_2 emissions	0.4542
Resident income	0.3722
Workforce size	0.3722

The results of the sensitivity analysis show that there are significant differences in the degree of contribution of different parameters to the objective function, with the number of tourists being the most influential factor in the sustainable development of tourism. Among the five parameters, the number of tourists has the highest sensitivity to the objective value, indicating that tourism income is the core factor influencing the overall objective value; the sensitivity of carbon dioxide emissions is lower, but they play a secondary supportive role in the optimization process; and the sensitivity of the residents' income and the size of the labor force is the lowest, which may be due to the small fluctuation of their historical data.

In order to show the results of the sensitivity analysis more intuitively, this paper visualizes the results of the sensitivity analysis in bar charts, which directly show the degree of influence of each parameter on the objective values. The results show that since the visitor number factor has the greatest impact on achieving the comprehensive optimization goal of tourism in Juneau, priority should be given to changes in visitor numbers when formulating policies. In addition, by dynamically adjusting the weights, policymakers can be provided with a basis for trade-offs between multiple objectives to optimize policy effects.

3.4. Revenue Expenditure Strategy

According to the results of sensitivity analysis of the multi-objective dynamic optimization model, the increase in the number of tourists has a significant impact on the government revenue, and the imposition of additional tourist tax produces an effective control on the sustainable use of tourism resources. This paper quantifies the relationship between the number of tourists and income, the number of tourists and environmental impacts by establishing a system dynamics model [11] that includes the number of tourists, income, expenditure, and environmental impacts, and the relationship between the variables in the system dynamics equation is expressed as follows.

$$\frac{dR}{dt} = b_1 N(t) \tag{5}$$

$$\frac{dE}{dt} = a_1 N(t) - a_2 I(t) \tag{6}$$

Where R(t) is tourism revenue, N(t) is the number of visitors, E(t) is environmental impact, and I(t) is infrastructure investment, a_1, a_2, a_3 are the weighting factors.

According to the importance level, this paper sets parameter values for these relationships: (1) set $b_1 = 100$, i.e., for every additional tourist, the tourism income increases by 100 yuan; (2) set $a_1 = 0.01, a_2 = 0.005$, i.e., for every additional tourist, the environmental impact increases by 0.01, and for every additional unit of investment in infrastructure, the environmental impact decreases by 0.005. finally, using the Runge-Kutta method [12] to solve the system of differential equations and get the numerical solution of each variable over time. By comparing with the actual data and based on the results of the model analysis, the optimal decision-making recommendation is made: it is recommended that 30% of the additional revenue be used for infrastructure investment and 50% of the additional revenue be used for environmental protection, which is conducive to the maximization of the goal of sustainable tourism.

Finally, this paper further represents the relationship between different variables in phase space trajectory diagrams, and the visualization results are shown in Figure 8.

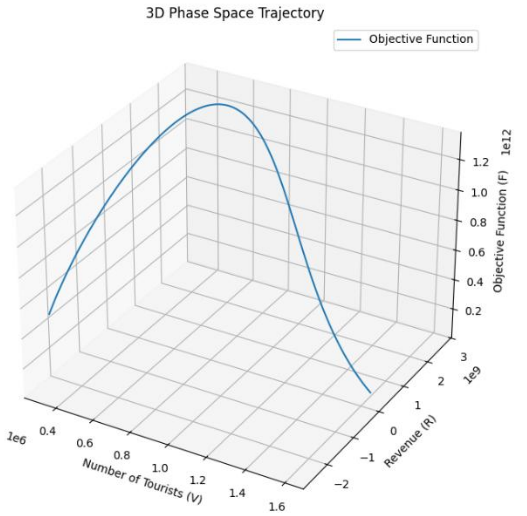

Figure 8. Phase space trajectory diagram

4. Conclusions

To realize the sustainable development of tourism, this study establishes a multi-objective optimization model and supplements it with a dynamic weight adjustment mechanism, which flexibly changes the weight values to get the optimal solution, and then conducts sensitivity analysis on the results, from which the number of tourists is the biggest influence factor of the model. Then the results were subjected to sensitivity analysis, which led to the result that the number of tourists is the most influential factor in the model, and the sustainable tourism development model based on dynamic planning with multi-objective optimization was successfully constructed. This study establishes the model by assigning dynamic weights to each objective function, which makes the model applicable to multiple scenarios of income optimization or environmental priority, as well as multiple stages of optimization, such as short-term and long-term optimization, and fully takes into account the influencing factors of Juneau tourism, such as income, environment, residents' satisfaction and crowdedness, and comprehensively covers the key indicators of tourism management, and provides a model for sustainable tourism development. It provides a useful method for the sustainable development of tourism and helps to solve the problem of over-utilization of resources.

This model, however, also has some weaknesses. Considering that the linear assumption of energy consumption and carbon emission in the formulation of the objective function of this model ignores the complex nonlinear correlation, the fmincon optimization method is limited in its ability to deal with the nonlinear problem, and it may not be able to efficiently solve the complex objective function. In further investigation and research, nonlinear correlation modeling can be considered, and nonlinear or interaction effects can be taken into account when constructing formulas for optimized returns $(R(N,T))$, energy consumption $(E(N,T))$, etc., such as using quadratic functions or machine learning models to fit more complex relationships. In addition to this, attempts can be made to introduce advanced optimization algorithms that are more suitable for nonlinear problems, such as genetic algorithms and particle swarm optimization, which in turn can adjust the convergence tolerance or the number of iterations to improve the efficiency and accuracy of the solution. In the future, there will be more explorations in the aspect of sustainable tourism to get more efficient strategies.

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