| Problem Chosen | 2025 MCM Summary Sheet | Team Control Number |
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| B | | 2512282 |

Tourism is on the rise in Juneau. For the second year in a row, Juneau received a record number of tourists with 1,677,935 cruise ship passengers arriving in the city during the year of 2024. [1] The increasing number of tourists each year indicates the future of Juneau's tourism industry to be **full of potential**.

However, as the problem statement finds, tourism can have its downsides. The number of resources in Juneau is limited and, if the number of tourists exceeds what Juneau can handle, the ecosystem will take a toll towards an unsustainable future. That is why **sustainability**, on both the **environment** and **local society**, is a factor that must be considered when outlining the future of Juneau's tourism industry.

Therefore, this paper discusses an approach to finding a sustainable solution for tourism in not only Juneau, but also other locations impacted by overtourism. By using two metrics, an **environmental index** and a **satisfaction index**, we can measure how much a set number of tourists affect the sustainability of a certain factor. These factors include air pollution, water demand, trash and waste produced, effects on the local economy, and civilian dissatisfaction.

We first measure the impact of the set number of tourists on Juneau within a specific factor. However, after we obtain these measurements through different methods, we must develop a common unit to combine our factors into a final value. We use a **common range** from zero to one, with both representing the extremes of either very sustainable or very unsustainable. Exactly what these extremes mean when applied to each factor vary across each individual variable.

We then use our model to find the optimal number of tourists. By using **N** as a variable for the number of tourists in Juneau, our model calculates to what extent the tourists are sustainable for the city as a whole. We also find what to set the **additional fees** imposed upon tourists in order to discourage enough people from visiting Juneau and reach that optimal number of tourists.

Finally, we discuss the ways our model can be extended further. We discuss the ways the revenue from the additional fees can be spent to improve the city's sustainability in the future. We also discuss ways our model can be applied to tourist attractions beyond Juneau.

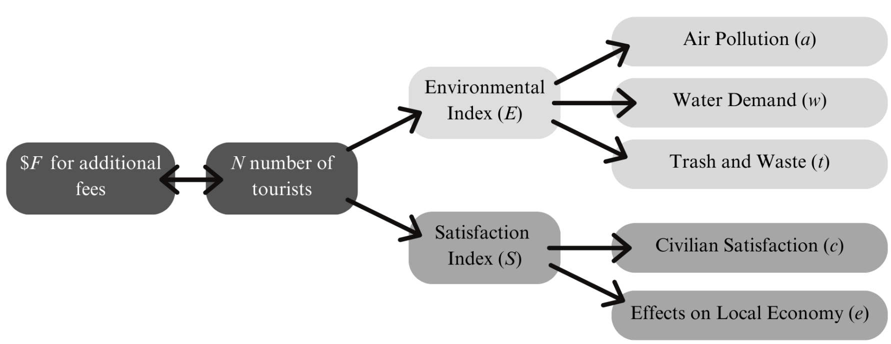


Figure 1: *Flowchart of Model Concepts*

# Sustainable Tourism: A Mathematical Approach

Team Control Number: 2512282

May 4, 2025

# Contents

# 1 Introduction

Tourism is a double-edged sword. While it often comes with a significant boost to the local economy, it can come at a hefty price for both the locals and the economy.

However, the aid of tourism in a regional economy cannot be understated. It is why many cities vie for the chance to host the World Cup or the Olympics. For an example, take Rio de Janeiro in 2016. While the influx of tourists allowed the rapid development of new infrastructure, the city could not keep up with the needs of the fans. The 2016 Olympic Games produced 17,000 tons of waste, used 29,500 gigawatts of electricity, and consumed 23,500 liters of fuel. The lasting impact of the games was devastating, contributing 3.6 million tons of carbon and polluting Guanabara Bay indefinitely. [2]

Although Juneau, the capital city of Alaska, has not yet faced such challenges, they are bound to at their current rate. Juneau's glaciers are melting, their carbon footprint is rising, their congestion is reaching alarming heights, and the locals are growing restless.[3] As a result, sustainable tourism is essential to preserve the beautiful city of Juneau.

## 1.1 Outline of Approach

Through the use of our optimization model, we aim to determine the optimal number of tourists for a sustainable tourism industry in Juneau using iterative search with our **primary model**. Then, we find the optimal additional fee that the government should implement to maximize the local economy while making tourism sustainable using a **secondary model**. Through our model, Juneau would be able to reap the benefits of tourism while ensuring sustainability in the industry. Submodels are used to model more complex behavior.

## 1.2 Assumptions and Justifications

1. **The current tourism industry in Juneau is unsustainable.** The current tourism industry is already unsustainable, with unaccounted hidden burdens on ecosystems. [4] Citizens are already becoming frustrated and protesting, and the situation will continue to escalate if the industry is not slowed down. [5] Therefore, we assume the optimal number of tourists for greater sustainability to be less than the current number of tourists.
2. **The additional demand on the environment is linear for each additional tourist.** We assume that the additional demand on the environment will be proportional to the number of tourists, since each tourist would use a set amount of Juneau's natural resources. Therefore, we convert all of our data to per capita to do this.
3. **The average number of tourists per day is 4383.** Annually, Juneau has over 1.6 million tourists. [1] This means that on average, 4383 visitors visit Juneau daily.
4. **The number of tourists must be a whole number.** In some cases, our metrics may spike or be discontinuous on a decimal point. While having a fraction may be more optimal in these situations, since it is impossible to have a partial tourist, we discard these solutions.

# 2 Variables and Definitions

| Variable | Definition |
|---|---|
| $F$ | Additional Fees |
| $N$ | Number of Tourists |
| $E$ | Environmental Index |
| $S$ | Satisfaction Index |
| $a$ | Air Pollution |
| $w$ | Water Demand |
| $t$ | Trash and Waste |
| $e$ | Effects on Local Economy |
| $c$ | Civilian Dissatisfaction |

Table 1: *A list of variables used within this model and their corresponding definitions*

We use capital letters for the main variables of our model, including our metrics and parameters. On the other hand, for the factors that are used to determine our metrics, we use lowercase letters. The next few sections go further into mathematical definitions of each variable, including setting constraints and values.

## 2.1 Parameters

The variable $N$ is the number of tourists per day. $N$ is the only parameter for the primary model to optimize sustainability. It is the basis for all the other variables, and the parameter to optimize for our primary model.

The variable $F$ is the tool that the Juneau government can harness to control the number of tourists. Using the price elasticity of tourism, one can compute the optimal fees to deter or encourage a certain amount of tourism. This is effectively the parameter the model is solving for in the secondary model.

## 2.2 Satisfaction and Environmental Indices

The variable $E$ is the index that represents the environmental damage that tourists cause. This index is computed by summing up its three subfactors — pollution, water, and waste.

The variable $S$ is the index that represents the overall satisfaction of the locals with a given number of tourists. Similar to $E$, this index is computed by summing the normalized effect on the local economy, $e$, and civilian dissatisfaction, $c$.

After normalization, the normalized values of each variable are summed to form the satisfaction and environmental indices. The environmental index decreases as the pollution, waste, and water usage increases, reflecting how the environmental damage accumulates as these factors get worse. Additionally, both indices are normalized again to a scale of 0-1 since both are equally important. The following equations are the general formulae for how to calculate each index. We give more detail for the calculations of each factor in *Factor Ranges.* (sect. 3)

$$E = 1 + \frac{(-a)+(-w)+(-t)}{3}$$
$$S = \frac{e+(1-c)}{2}$$

### 2.3 Factors

The amount of air pollution created by the $N$ number of tourists is represented by the variable $a$. Air pollution is represented by the $CO_2$ levels in the air.

The water demand necessary for the $N$ number of tourists is represented by the variable $w$ in liters. The water demand is not only the additional pressure from the tourists but also includes the normal amount of water demand from the populace of Juneau itself.

The additional trash and waste produced by the $N$ number of tourists is represented by the variable $t$. This waste includes solid matter as well as ordinary trash produced.

The effects on the local economy caused by an $N$ number of tourists is represented by the variable $e$. This factor is concerned with how many **local businesses** are aided by the tourism industry. It is represented by the number of additional businesses that tourism brings in.

Civilian dissatisfaction for an $N$ number of tourists is represented by the variable $c$. This factor is represented as a percentage that shows what percent of the local Juneau population is dissatisfied with the tourism industry. Note that when computing the satisfaction index ($S$), $c$ is subtracted from 1 to represent the percentage of civilians that are satisfied.

## 3 Factor Ranges

With our indices and factors in place, it is time to connect them into a singular model. For a given number of tourists arriving in Juneau, we need to assign a value to each of these factors to form their corresponding index.

This is why we set a common range from zero to one. It is, of course, unrealistic to add the raw numbers of the amount of water used to the percentage of Juneau's civilians who are dissatisfied. Therefore, we use this **range** as an **intermediary**, indicating to what extent is the number of tourists sustainable for each factor.

By **normalizing** our factor's raw number onto a scale, we have common values that are much easier to work with. We want to set the ends to the most extreme numbers, either **extremely sustainable** or **extremely not sustainable**. However, the way we set our range for each of our factors varies greatly; therefore, we create **submodels** for each factor, explaining how we set the upper and lower limits for each range below.

## 3.1 Environmental Index Factors

Our environmental index is focused on measuring the **usage and production of resources**. Ranging from air to water, to waste, our index should become more **sustainable** the **less** resources are used, and the **less** pollution there is.

Therefore, for this section, we set zero as the lower boundary, indicating the use of this factor is sustainable. We then set one as the upper boundary, indicating the use of this factor is the least sustainable it can be. However, in the environmental index, we average them and then **subtract** the result from one to represent the environmental **damage** as follows: $E = 1 + \frac{(-a)+(-w)+(-t)}{3}$

### 3.1.1 Air Pollution

For the air pollution's range ($a$), zero would represent no air pollution, while one would represent significant air pollution to become hazardous. Our lower boundary is already set to zero air pollution at all. Yet, when it comes to our upper boundary, we need to find data regarding the hazards of air pollution.

Our initial thought was to use data from Juneau's **greenhouse gas emission** reports to understand further the phenomenon. However, when the data we came across was far too low, we realized that Juneau's air pollution reports do not account for the air pollution caused by cruise ships passing through, the main polluters.

Therefore, we had to take a different approach. We first found the amount of air pollution each tourist on a cruise ship emits: 421.43 kg of $CO_2$ each day. [6] Then, we found how much $CO_2$ would need to be present in the air to cause headaches, fatigue, poor concentration, and nausea. As written by the $CO_2$ Meter, we found that it takes 0.2-0.5% of $CO_2$ in the air to cause the above-listed symptoms. [7] We take the average of the range, 0.35% $CO_2$, and use it to find our upper limit.

Using this statistic, we need to calculate 0.35% of all the air in Juneau to find a **concrete mass** of $CO_2$ as our final upper limit. Beforehand, however, we must find the mass of all the air on top of Juneau's area. Given the average altitude of Juneau is 374 meters above sea level [8] and the average temperature is 5.5 degrees Celsius [9], we use a pressure calculator to find the air pressure on Juneau to be **96,764.35 Pa**. [10] With the land area of 8430.411 square kilometers [11], we use a pressure calculation to find the mass of the air as shown below:

$$P = F/A$$
$$96764.35 \text{ Pa} = ma/8430.411 \text{ km}^2$$
$$\frac{96764.35\frac{\text{N}}{\text{m}^2}}{9.8\frac{\text{m}}{\text{s}^2}} \cdot 8430.411km^2 \cdot \frac{1000^2m^2}{1km^2} = m$$
$$m = 9873.9133\frac{(kg\cdot\frac{\text{m}}{\text{s}^2})\cdot s^2}{\text{m}^3} \cdot 8430.411 \cdot 10^6m^2$$
$$m = 8.3241 \cdot 10^{13}kg$$

Given we know the mass of all of Juneau's air, we can set our upper limit to $2.9134 \cdot 10^{11}$ kg of $CO_2$, or 0.35% of the air's mass. Given an $N$ number of tourists in Juneau, we use the following equation to scale our raw number onto our common scale:

$$a = \frac{N \cdot CO_2 \text{ emissions per capita}}{\text{Maximum } CO_2 \text{ emissions}} = \frac{N \cdot 412.43kg}{2.9134 \cdot 10^{11}kg}$$

### 3.1.2 Water Demand

For the water demand's range ($w$), zero would represent no water needed, while one would represent the demands of tourism overwhelming Juneau's water supply.

Similar to air pollution, our lower boundary is already set to zero water needed. Yet again, when it comes to our upper boundary, we need to find data on Juneau's **water supply**. We set the upper limit to be equal to how much water is in Juneau, since if the demand exceeds the supply, the amount of water used would still be the same as there is no more water to be used.

Finding data for this factor is far more straightforward than finding data for air pollution. From Juneau.org, we find that Juneau has 1.2 billion gallons of drinking water per year for use. [12] We want to transfer these numbers into the form of per day, since we've established that at the beginning of our paper. Converting our data, we calculate there is on average 12,445,189.3 liters of water available to be used each day.

However, we need to subtract the amount of water **Juneau's civilians** need from the total available water. On average, the average person uses 384.2 liters of water per day. [13] Multiplied with Juneau's population of 31,337 people [14], we find that Juneau civilians would use 12,039,675.4 liters per day. By subtracting the city's water demand from Juneau's entire supply, we find that tourists will have 405,513.9 liters of water left over to be used; as such, we set this as our maximum.

With our maximum found, we now need to find how much water each tourist uses each day. In a study by Gössling *et al.*, the estimated peak water demand for a tourist is 300 L in the U.S. [15] As such, we use this number for our per capita demand from a tourist. With this information, we can combine all the data to form this equation:

$$w = \frac{N\cdot\text{Water demand per capita}+\text{Population of Juneau}\cdot\text{Water demand per capita of Juneau}}{\text{Maximum water usage}} = \frac{N\cdot 300+(12{,}039{,}675.4)}{12{,}445{,}189.4268}$$

### 3.1.3 Trash and Waste

For the trash and waste's range ($t$), zero would represent no waste produced, while one would represent the capacity of Juneau's landfill being reached.

Again, our lower boundary is set to zero waste produced. When it comes to our upper boundary, we need to find data on Juneau's landfill capacity to represent the supply of Juneau's services being met.

We indeed acknowledge that, even if Juneau's **landfill capacity** is reached, tourists can keep coming and can keep producing more waste. This means that, when converting to our range, the factor for the $N$ number of tourists could exceed one, not satisfying the ends being the most extreme scenarios as claimed earlier. However, if Juneau's tourists are indeed producing more waste than it can handle, our model has the justification to list this factor as extremely, extremely unsustainable. This means that, since it would be unsustainable for the tourists to produce more waste than what Juneau can handle, our model should be able to exceed the upper boundary of our range to indicate a dire crisis.

From there, the math is simple. The EPA finds that on average, one person produces 2.2226 kg of waste per day. [16] Moreover, Juneau's landfill — **the Capitol Disposal Landfill (CDL)** — can handle 74563.33 kg of waste each day. [17] From these two numbers, we can normalize the amount of waste using the following equation:

$$t = \frac{N \cdot \text{Waste produced per capita}}{\text{Maximum waste production}} = \frac{N \cdot 2.2226kg}{74563.33kg}$$

## 3.2 Satisfaction Index Factors

Our satisfaction index, $S$ is focused on measuring the **happiness and mood of Juneau's civilians**. From local businesses to everyday civilians, our index should become more **sustainable** the happier Juneau's civilians are.

Therefore, for this index, we set one as the upper boundary, indicating that civilians are the happiest that they can be about Juneau's tourism industry. We then set zero as the lower boundary, indicating the civilians are as dissatisfied as they could be with the tourism. Since $c$ represents the dissatisfaction, we subtract $c$ from 1 to show how many civilians **are satisfied**, given our results are in a percentage form. We average the factors at the end and add the results to represent the Satisfaction Index as follows: $S = \frac{e+(1-c)}{2}$

### 3.2.1 Effects on Local Economy

For this factor's range, zero would represent civilians gaining no money at all, while one would represent civilians gaining the most amount of money.

Unlike what we did with previous factors, we do not need to find the positive extreme as to what's the most money local businesses can earn. This is because the most money businesses can earn would be $N_{maximum}$, the most tourists per day that have once come to Juneau multiplied by the money tourists spend each day - $\text{Money}_{tourists}$. In addition, the money local businesses would earn from an $N$ number of tourists would be $N \cdot \text{Money}_{tourists}$. By normalizing our data to our scale, we would receive the following equation:

$$e = \frac{N \cdot \text{Money}_{tourists}}{\text{N}_{maximum} \cdot \text{Money}_{tourists}} \text{ which would be simplified to } \frac{N}{\text{N}_{maximum}}.$$

Our simplified equation makes sense. The more tourists there are, the more money is put into local businesses and more economic exchanges happen within Juneau's local economy. This means that the greater the number of tourists is, the more money enters the economic flow of Juneau, and the more sustainable Juneau is with an improved economy. Therefore, a greater number of tourists would increase its standing and position on the normalized scale for the local economy.

### 3.2.2 Civilian Dissatisfaction

For the civilian dissatisfaction ($c$) factor's range, zero would represent civilians being extremely happy, while one would represent civilians being the most frustrated. This factor is less concerned about the local businesses being preoccupied with money and more about the local civilians who have varying roles in society.

Unlike all previous factors, there is no evidence suggesting that this factor has a **linear correlation** between the number of tourists and the overall dissatisfaction of the population. Locals have complex points of view, ranging from not only profits but also congestion in public spaces, increased costs to supplies, and noisy foreigners. Therefore, we must gather sufficient data before jumping to finalize the correlation between tourists and civilian dissatisfaction.

To gather data, we rely on the **CBJ Tourism Surveys**. This is a survey conducted to learn about how public views on the tourism industry in Juneau change from year to year. However, this survey was only conducted a few times in 1998, 2002, 2006, 2021, 2022, and 2023, and there are no other similar surveys conducted specifically on Juneau's civilians. This means that this is all the data we get to work with when regarding civilian satisfaction or dissatisfaction.

Within these surveys, however, we can find data for each year on the percentage of survey participants who believed the costs of tourism outweigh the benefits, indicating the participants are frustrated with the tourism industry and do not believe in its benefits.

To find a correlation, we must also gather data on the average number of tourists per day visiting Juneau. We excluded the data from 1998 since we could not successfully find the average number of tourists visiting Juneau each day 27 years ago.

We list our findings from the years 2002, 2006, 2021, 2022, and 2023 below as in both a table and also a graph:

| **Year** | **% of Civilians Dissatisfied** | **Average # of Tourists Per Day** |
|---|---|---|
| 2002 | 29 [18] | 2,032.9 [19] |
| 2006 | 32 [18] | 2,605.5 [19] |
| 2021 | 30 [20] | 341.4 [21] |
| 2022 | 32 [22] | 3,287.7 [21] |
| 2023 | 25 [23] | 4,490.1 [1] |

Table 2: *Civilian Dissatisfaction Data Organized Across Year, Percentage, and Tourist Numbers*

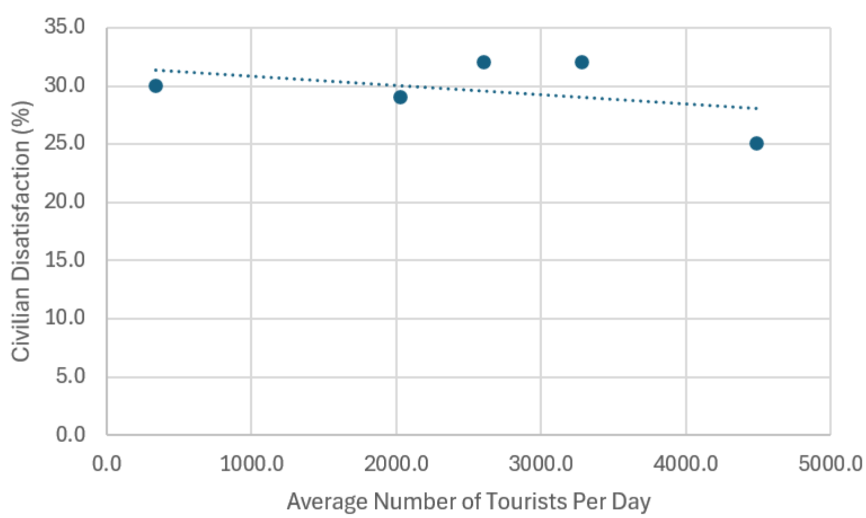


Figure 2: *Correlation of Number of Tourists with Dissatisfaction in 2002, 2006, 2021, 2022, and 2023*

Looking at our graph, we can see that the data from 2021 is a pretty big outlier. It does not follow the curved pattern the other data points do, and it isn't anywhere near the location of the other data points on the graph.

We pinpoint the cause of this problem to be the **COVID-19** epidemic. COVID-19 had a massive impact on travel around the world, severely hindering the global tourism industry by restricting tourists from traveling. [24] We realize that locals in 2021 may have been concerned with tourists traveling and spreading diseases across the world, something that tourists are not as concerned about in other years. Therefore, understanding that such concerns are not prevalent each year, we remove the data from the 2021 survey to ensure consistency with the future's main concerns, what our model is trying to predict here. The graph without the data point from 2021 is shown below:

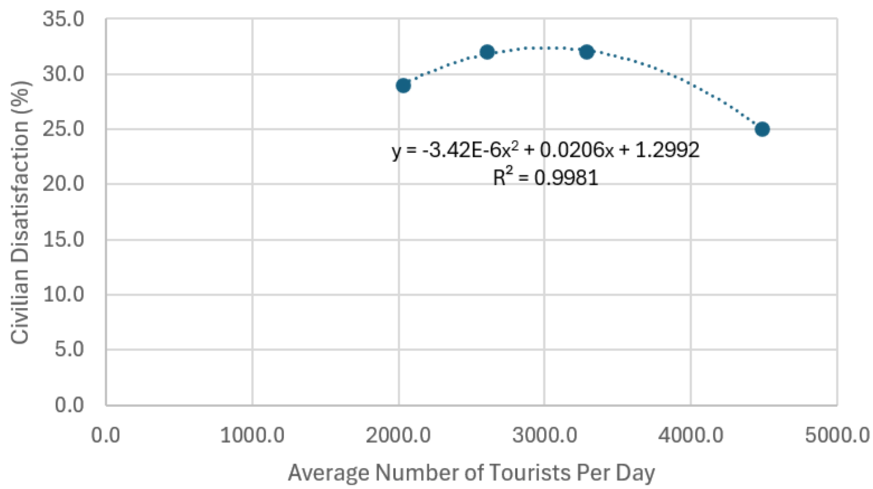


Figure 3: *Correlation of Number of Tourists with Dissatisfaction Excluding Data From 2021*

Without 2021's data, we have a clean quadratic where the points align themselves. Moreover, the **quadratic regression**'s R-squared value is 0.9981, indicating the regression has an extremely tight correlation with the data points we gathered. Therefore, we can be confident that our regression model can be representative of the future's correlations between an $N$ number of tourists and civilian dissatisfaction.

Converting our raw data into our range is not as complex as for the other factors. Given our output is already in a percentage form, we simply need to divide the y-value, a percentage of many locals are dissatisfied, by 100 to normalize the factor into our scale. Using our regression model from above, we can use the following equation to determine $c$:

$$c = \frac{-3.42e{-6} \cdot N^2 + 0.0206 \cdot N + 1.2992}{100}$$

However, given that this is a quadratic equation, there are points that will have a y-value, or dissatisfaction percentage, lower than zero. This doesn't make sense, as it's impossible to have greater than 100% of a city's population satisfied with the tourism industry. Therefore, if the y-value is negative, we set the variable $c$ as zero instead.

# 4 Model

The model we designed is meant to optimize two major parameters: the number of tourists, and the additional fees a government can set. This is because the satisfaction and environmental indices - which are the key dependent variables to optimize - depend solely on the number of tourists that place additional strain on Juneau. The satisfaction and environmental indices are critical, as they will determine if tourism is sustainable in Juneau, the main goal the entire model is aiming for. As such, the model is split into two parts: one to optimize sustainability, which is our **priority**, and another to optimize the profits as a **secondary motivation**.

## 4.1 Primary Model

Our model aims to first ensure maximum sustainability. It optimizes the number of tourists such that environmental damage along with the dissatisfaction of beneficiary businesses and other locals are minimized.

These are quantified using a variety of factors for each. For the environmental damage, three factors - pollution, water, and waste - are used to form $E$, the environmental index. For satisfaction, the number of additional consumers, tourists, and the dissatisfaction of locals modeled using surveys are used to form $S$, the satisfaction index.

In the first half of our model, we define the minimum and maximum values of each factor as shown in *Factor Ranges*. (sect. 3) This allows us to normalize each factor, allowing us to accurately combine them in a way such that all factors are represented equally in each index. The sign of the ranges reflects the negativity or positivity of each variable. Dissatisfaction, pollution, water, and waste are normalized to a range of 0 to -1, as these variables hurt the sustainability of the tourism industry in Juneau. However, the number of additional consumers is normalized to a range of 0 to +1, since for the local economy to stay stable through support from the tourism industry, tourism must be able to bring in additional consumers. In this instance, more tourists can cause a positive change.

The number of tourists is the **independent variable**, which we are trying to change in the primary model to optimize the main dependent variables of sustainability. We optimize the sustainability indices by using the **maximin** — maximizing the minimum index. Maximin is used as total sustainability is not the primary objective — the primary objective is to ensure that **both** the dissatisfaction and environmental damage are minimized to achieve sustainable tourism. By maximizing the smaller of these two, we ensure that both indices are acceptable, not just one index becoming more important and completely outweighing the other.

After optimizing for the optimal number of tourists to maximize the minimum index, we then use the secondary model to calculate what changes the government can make to achieve said optimal number, by creating a cap on the number of daily visitors and additional fees to economically discourage tourism via taxes and visitor fees.

## 4.2 Secondary Model

In the secondary model, we calculate what the government should do to achieve the optimal number of tourists for sustainability by deriving a general formula. In the process, revenue is also optimized for this specific number of tourists. It is important to note that this model is another **optimization** on top of the primary model, so sustainability is **always optimized first** before using the secondary model. The emphasis is placed on sustainability, not revenue; however, revenue is also something that needs to be considered in our model.

After finding the optimal number of tourists, we set a daily limit of the number of tourists equal to the optimal $N$. This ensures that the number of tourists we let in will never exceed the optimal $N$ and cause excessive environmental damage. Since we want to decrease the number of daily tourists, there will always be more tourists that **wanted** to enter Juneau than the limit.

After setting the limit, we want to maximize the revenue. We can raise or decrease the price of entering Juneau via $F$, or additional visitor fees. This way, by increasing or decreasing the expenses tourists have to pay, our model can encourage or discourage **potential tourists** from entering Juneau. Further detail is modeled in *Submodels*. (sect. 4.3)

After finding $N$, we optimize $F$ to have the number of people who want to go to Juneau equal to the number of people we will let in. This is good as not only will revenue be maximized, but all tourists who *want* to enter Juneau *can* enter Juneau.

By using the primary and secondary models together, we create large profits for the government of Juneau without compromising the creation a sustainable tourism industry.

## 4.3 Submodels

Specifically for the factor of local dissatisfaction ($c$), a more complex model was used as the relationship between the number of tourists and the dissatisfaction of the locals is more nuanced than a linear model. After looking at the data, a quadratic model was decided on with the equation which was computed. The equation we used to model $c$ is derived from Sect. 3.2.2, and its equation is as follows:

$$c = -0.00000342 \cdot N^2 + 0.0206 \cdot N + 1.2992$$

To model how tourism decreases as prices increase in our secondary model, we use **price elasticity** to compute how much tourism decreases for every price increase. The price elasticity of tourism averages to around **-1.545**, meaning that for every 1% increase in price, tourism decreases by 1.545%. [25] With this knowledge, and the fact that the average tourist spends \$232 in Juneau per day and \$400 to travel to Juneau, we can create a general equation. (Assumption 3 tells us that the number of daily visitors is 4383.)

$$\text{Percent Decrease in Tourism} = (N - 4383)/4383$$
$$\text{Price Increase in Percent} = \frac{\text{Percent Decrease in Tourism}}{\text{Elasticity}}$$
$$\text{Absolute Price Increase} = \text{Price Increase in Percent} \cdot \text{Price Per Person}$$

By substituting in the **nominal values**:

$$F = \frac{((N-4383)/4383)}{-1.545} \cdot (232 + 400)$$

The above formula models the additional fees that Juneau should charge to have the optimal number of tourists. After finding the optimal number of tourists, we can use this formula to find the optimal additional fees to charge.

## 4.4 Model Implementation

Every index and primary operation of the model can be simplified to a system of equations easily. The primary model is centered around the indices $S$ and $E$ - the satisfaction and environmental indices. For both of these, they are equations that have a **single independent variable**: $N$, the number of tourists. Recall that the definitions for $E$ and $S$, our primary metrics are:

$$E = 1 + \frac{(-a + -w + -t)}{3}$$
$$S = \frac{e + (1 - c)}{2}$$

By substituting each variable's definition, it is clear that the number of tourists is the only independent variable for these indices, so we only need to optimize the number of tourists.

$$E = 1 + \frac{(-\frac{N \cdot 421.3}{291{,}340{,}000{,}000} + -\frac{(N \cdot 400) + (30{,}000 \cdot 383)}{12{,}445{,}000} + -\frac{N \cdot 4.9}{6{,}000{,}000})}{3}$$
$$S = \frac{(\frac{N}{4383}) + (1 - (-0.00000342 \cdot N^2 + 0.0206 \cdot N + 1.2992))}{2}$$

The primary model then iteratively searches all values of $N$ and finds the best $N$ value such that the **minimum** of the two indices is **maximized**. Since the equations are relatively simple, computing every possibility is fast enough to calculate the optimal number of tourists to allow in. Using an optimization algorithm may cause issues as the model grows, as the functions may not cause issues with other optimization algorithms such as gradient descent if it gets stuck in a local maximum.

Using this iterative method is simple but ensures that all possibilities are accounted for. After identifying the optimal $N$, the secondary model calculates the optimal additional fees to charge.

The ranges for $N$ to iterate over is a **hyper-parameter**, specified before the model is used. In the case of Juneau, the range is from 0 to 4383, the average daily number of tourists (see: assumption 3), as we know we will not surpass this number since tourism is already unsustainable in Juneau.

The following equations are the central equations used in the model. The primary model optimizes for $N$, and the secondary model calculates what additional fees to charge using $N$:

*Primary Model*

$$S = \frac{(\frac{N}{4383}) + (1 - -0.00000342 \cdot N^2 + 0.0206 \cdot N + 1.2992)}{2}$$
$$E = 1 + \frac{(-\frac{N \cdot 421.3}{291{,}340{,}000{,}000} + -\frac{(N \cdot 400) + (30{,}000 \cdot 383)}{12{,}445{,}000} + -\frac{N \cdot 4.9}{6{,}000{,}000})}{3}$$

*Secondary Model*

$$F = \frac{((N - 4383)/4383)}{-1.545} \cdot (232 + 400)$$

After finding $F$, the government of Juneau can then set the additional fees to charge to maximize revenue and ensure that the number of tourists entering Juneau is sustainable. See Figure 4 for a flowchart to visually depict the above process.

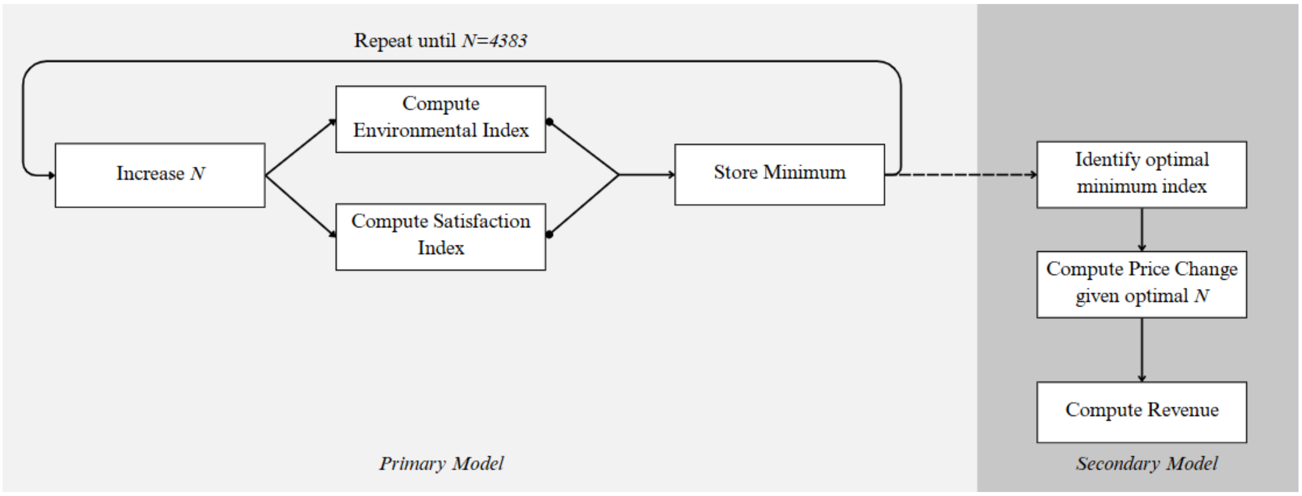


Figure 4: *Flowchart of Model Mathematical Process*

# 5 Results

## 5.1 Optimization Results

Since Juneau is currently unstable, we assume that we want to decrease the number of tourists. As such, we only iterate until the current daily average number of tourists: 4383 per day. [1]

The model finds that the optimal number to ensure that the environment, locals, and the local economy are all succeeding is **2606 tourists**. At this number, both indices reach roughly **0.6538**, which is the **equilibrium**. Any more tourists and the environment will suffer more, and any less local businesses would lose too much business.

To achieve this number of tourists, the daily limit should be set to only 2606 people, and additional fees of **$165.85** should be set — whether it's from additional taxes or new visitor fees. [25] Additionally, the estimated revenue will be around **$2,079,190 per day**, which can still hugely benefit the local society. Although there will be fewer tourists, the tourism industry will still be able to bring in benefits for Juneau.

## 5.2 Sensitivity Analysis

After the optimization, more insight can still be gleaned by performing a sensitivity analysis to understand the interactions between variables. One of the most important interactions to analyze is our cost function — the maximin that combines both indices. Figure 5: Minimum Index vs. Tourists is a graph of the maximin function as a function of the number of tourists.

The correlation behaves like a **piecewise function**, which is expected - if the satisfaction index rises above the environmental index, the environmental index becomes the index to optimize. However, something interesting to note is that the minimum index decreases. This is significant as it shows how as the number of tourists increases after a certain point, the overall sustainability of tourism decreases given the environment heavily suffers.

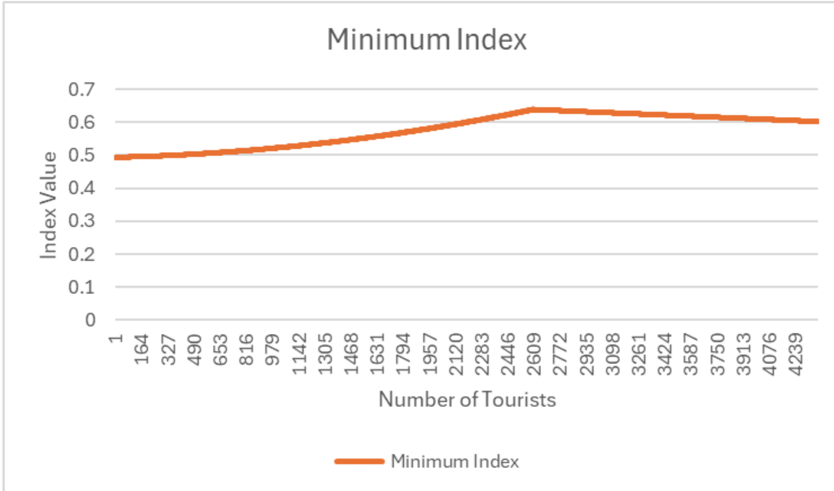


Figure 5: *Correlation of Minimum Index v.s. Number of Tourists*

This effect can be more clearly shown in Figure 6. Initially, the satisfaction index is lower as the local economy gains no benefit. As the number of tourists increases, the satisfaction of the local businesses increases until the environmental index outweighs the satisfaction index. The **equilibrium point**, where both indices are equal, is 2606 tourists, which is the optimal number as any change to this number would decrease either index further. Tourism hurts the environment, but it has a net positive impact on the satisfaction of Juneau's citizens. By further breaking the factors down, we can analyze these indices in more detail.

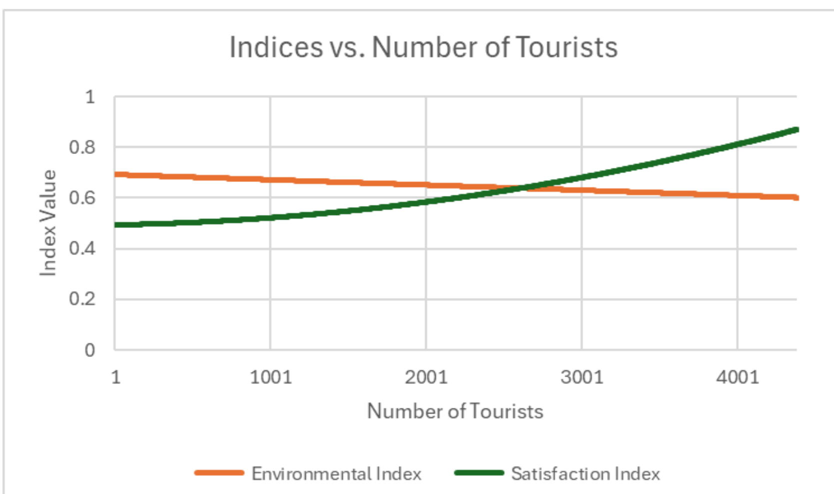


Figure 6: *Correlation of Sustainability Indices v.s. Number of Tourists*

At the equilibrium point of 2606 tourists, we can analyze which factors cause the most harm or the most benefit. In Figure 7, we can see that water pressures play a huge part in the environmental index, which demonstrates that the primary environmental damage caused by tourists is the **additional stress** placed on their water sources. For the satisfaction index, both dissatisfaction and local economic benefits are relatively close to each other, which shows how difficult it is to balance the satisfaction of businesses and locals.

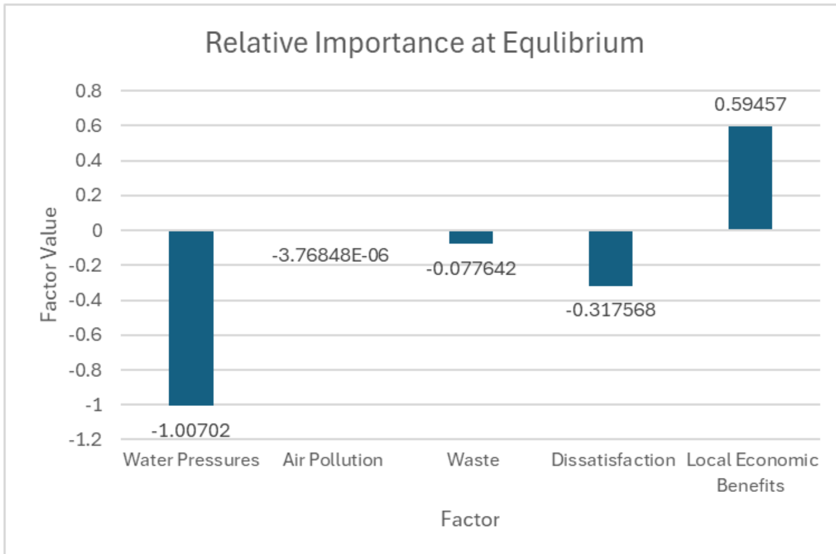


Figure 7: *Relative Importance of Factors at Equilibrium*

We can analyze how each factor would change by looking at their trends in Figure 8. As the number of tourists increases, water pressures steadily increase, along with waste. Waste and water pressures increase with a similar slope, which shows how as the number of tourists increases steadily, waste will start to become an issue along with water pressures. However, air pollution is extremely low relative to all the other factors; as the number of tourists increases, air pollution also increases at a slow pace. As such, air pollution can be discounted unless the number of tourists increases at a staggering rate.

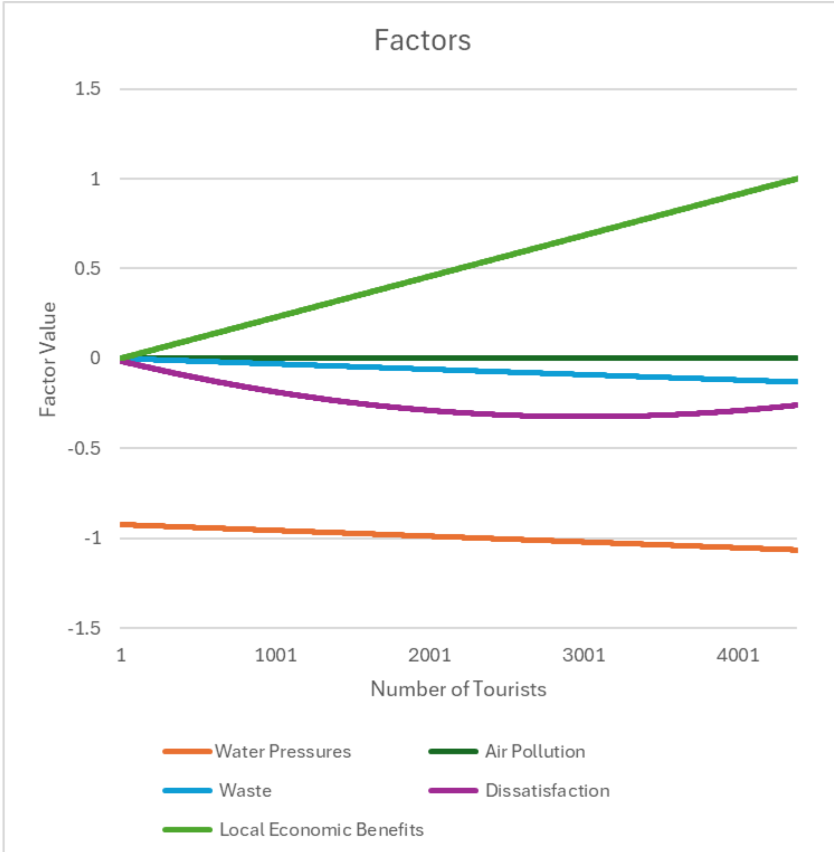


Figure 8: *Relative Importance of Each Factor vs. Time*

### 5.3 Key Insights

- The optimal number of tourists to allow for Juneau, Alaska is **2606 tourists**, which can be achieved by using additional fees of **$165.85** per person per day.
- Even at 2606 tourists, the revenue generated by the tourism industry is still a large sum: **$2,079,190 per day**. Tourism can still benefit the local economy while being sustainable.
- The **most important factor** to account for is the **additional water pressures** that tourism places on Juneau's water supplies.
- Air pollution produces a **negligible effect** on Juneau's environment and can be discarded.
- Initially, the economic benefits of tourism **outweigh** the environmental impact, but sustainability hinges on **having a balance** of both economic and environmental sustainability.

# 6 Memo

To: The Tourist Council of Juneau, Alaska.
From: Team Control Number 2512282, from the Mathematical Competition in Modeling.

We are pleased to announce the progress of our model for a sustainable tourism industry in Juneau! We have collected and examined the various factors within the tourism industry, and we have combined them to gain a comprehensive form of measurement. These factors vary under the indices of environmental sustainability and societal sustainability.

We have recently developed a model accounting for the demand for resources of tourists, the production of waste, and the happiness of Juneau's civilians in reaction to the number of tourists. We want to measure to what extent the tourism industry affects regional sustainability measures, and how that extent changes depending on the varying number of tourists in Juneau.

Of course, we should never add kilograms of water to the percentage of happiness among Juneau's citizens. That is why our model uses a scale from zero to one for all our factors, allowing a common unit across our entire model. Setting zero and one as either extremely sustainable or unsustainable, we find how sustainable a factor is with an $N$ number of tourists and place it upon this scale.

The way we set our extremes (zeros and ones) and how we place our sustainability measurements and calculations onto this scale vary greatly. However, in the end, we tally our factors up into their respective indices and then add both indices to obtain a final result. We want our result to be as large as possible, and we do so through constant result iterations of different values for the $N$ number of tourists.

By trying multiple values of $N$ within our model, we find the value of **2,606 tourists** per day on average as the most sustainable for Juneau. This number of tourists does not use up a lot of Juneau's resources, while also substantially helps Juneau's local businesses and civilian satisfaction on Juneau's tourism industry.

To optimize the outcome of 2,606 tourists for a sustainable tourism industry, we recommend the Tourist Council of Juneau to alter the additional fees imposed upon tourists. After all, the cheaper the additional fees are, the more tourists will come; therefore, we recommend increasing the additional fees to decrease and control the $N$ number of tourists.

Through our model, we estimate that additional fees of **$165.85** per tourist would funnel the number of tourists down to 2,606 each day. [25] This would increase the Tourist Council's revenue to **$2,079,190** per day, with plenty of money that can be used to improve the city's infrastructure and lifestyle.

Juneau's tourism industry has an incredible amount of potential. We hope that this model helps efforts to increase the industry's sustainability, while also providing the joys of Juneau to its tourists. And so, please let us know if you have any questions or concerns, and we look forward to further cooperation!

# 7 Model Extension

Although our model is based in Juneau, Alaska for this paper, our model can be applied to further tourist destinations. Our model can help encourage sustainable tourism industries across the world, either by promoting the tourism industry or limiting it. Moreover, the money we gain from the additional fees can be used to further promote sustainable tourism. We cover these topics in this section regarding **extensions** to our model.

## 7.1 Extrapolation

Our model has multiple factors that can be applied across multiple tourist attractions. The concerns for air pollution, water usage, waste production, local businesses, and regional approval are common across the world. However, in some places, some of these concerns matter more than others; hence, we must introduce a mechanism to further emphasize specific factors over others.

For example, take the island of **Aruba**. Despite being a small island, it is the most visited nation in the Caribbean, with the highest tourist return rate. [26]

However, its immense tourism industry has started to take a toll on the landscape. Lacie in 2018 reported Aruba's top concerns to be solid waste management and environmental damage from plastic pollution along its coastlines. Lacie pointed out that the cause for these consequences is tourists littering their trash along Aruba's coastlines, an action that must be stopped. [27]

Because of its current polluted state, Aruba must prioritize cleaning its polluted water from the effects of the tourism industry. We can account for hat in our model under the section for trash and waste, represented by the variable $t$. Unlike how we set the upper boundary of $t$'s range by finding the landfill capacity for Juneau, we can adjust the upper boundary for Aruba's trash and waste to be equal to the current status of trash along its coastline. This is because, since Aruba is **extremely unsustainable** already with its poor waste management, adding any more trash to its coastlines would prove to be even further unsustainable.

From there, we can adjust the rest of the variables to Aruba by changing the numbers involved in the calculations. We would have to research the land area and elevation of Aruba for air pollution, the fresh water available for water demand, and the percentage of Aruban citizens who believe the costs outweigh the benefits for the tourism industry. Then, like previously, we would tally up the number of tourists to find the optimal number of tourists and how much the additional fees should be to reduce the number of tourists visiting Aruba.

That was in the case of reducing the tourism industry. In the case of increasing the tourism industry, our model would alter the ranges for our variables - specifically the section on the effects on the local economy.

For this, we take the example of **Mozambique's coastlines**. As an alternative to Thailand's Andaman Coast, Mozambique has stunning and unspoiled coastlines **full of potential**. [28] However, it does not have an immense tourism industry, meaning its local businesses can't get the full economic boost and amount of profit.

Our submodel on the local businesses accounts for this. We normalize our raw numbers to the most money local businesses have made in the past through the maximum number of tourists. Since Mozambique hasn't had as many tourists as Juneau in the past, its maximum number of tourists would be significantly less, reducing the size of its scale when summing up all the factors. This makes it easier to surpass the positive extreme of our scale, therefore boosting the satisfaction index by going over one and encouraging a greater number of tourists for a better tourism industry.

With the multiple numbers and inputs we can change and adjust, our model can represent and model the changing properties and problems **across countless tourist attractions**.

## 7.2 Profit Allocation

The problem statement asks us to form a plan for spending the revenue gained from the additional revenue. To control the number of tourists to a sustainable amount of 2,606, our model found the Tourist Council of Juneau would have to gain an additional revenue of **$2,079,190 per day**.

This is, frankly, a lot of money. 2 million dollars every day can be substantial in promoting sustainability in Juneau's tourism industry. Even when excluding the money tourists put into Juneau's local businesses, the additional fees imposed can and must be used towards the same goal for our paper.

As our model is prioritized with improving sustainability, the revenue gained should be therefore used to solve problems regarding poor sustainability. These problems on poor sustainability would be the five factors we've set in our model; however, since tourists are already helping local businesses through direct economic exchange and money can't buy the satisfaction of local civilians, our problems are limited to **environmental contamination** - air pollution, water demand, and trash and waste production.

With the immense financial budget to work off of, many government-funded projects can be implemented to help aid the environmental contamination of Juneau caused by tourists. For example, to deal with air pollution, the local government can expand urban forestry efforts to plant more trees within public areas. This is already happening in Washington D.C., where the local government aims by 2032 to have a **healthy tree canopy** [29] - something Juneau's local government can aim for.

The local government could also aim for **Carbon Capture and Storage (CCS) projects**. These projects aim to reduce carbon emissions and capture $CO_2$ in the air through **specialized infrastructure**. [30]

Moreover, to deal with water demand, Juneau's local government can support the **Water Reuse Action Plan** already supported by the USDA. The Water Reuse Action Plan aims to filter and reuse water, therefore reducing the total amount of water used from Juneau's supplies. [31] Juneau can implement this plan to decrease its water usage by reusing the water it uses for its tourists through **treatment facilities**.

Furthermore, to deal with trash and waste production, Juneau can fund beach clean-up projects to reduce the amount of trash along its shores. To an even greater extent, however, Juneau can help improve the lifetime of the **Capitol Disposal Landfill**. Unfortunately, the CDL currently has a lifetime of only 30 years, which is not an adequate duration of time if Juneau wants its tourism industry to be sustainable in the long term. However, money can be used to help extend its lifetime, allowing for the tourism industry to remain sustainable for a longer period.

# 8 Conclusion and Evaluation

## 8.1 Model Evaluation

### 8.1.1 Model Strengths

- **Depth.** With a variety of factors, our model can model a variety of different variables that affect the sustainability of tourism simultaneously, even accounting for their interactions.
- **Scalability.** Through the use of submodels, the primary model and secondary models can both be scaled to model even more complex behavior. The general idea will remain the same: identify a sustainable number of tourists, and then identify the action needed to attain this number.
- **Optimization.** Our model optimizes and finds the best parameters for *all* tasks — sustainability, revenue, and satisfaction of the local population. Through the iterative process, all possibilities are attempted, so there is a guarantee that the solution found is the best.
- **Focus on sustainability.** Through the use of a split model and maximin, sustainability is always modeled first as the priority. This ensures that whatever solution is found, will be a sustainable solution.

### 8.1.2 Model Weaknesses

- **Need for data.** This model requires a large amount of data to work effectively, especially for the ranges of each factor for normalization. This could be difficult if data is sparse or too outdated.
- **Extremely specific.** This model can only be set up for one location at a time. Since every locations' ranges and issues are different, research must always be conducted to determine which factors to utilize.
- **Process Complexity.** This model has an especially high amount of conversions, which create room for error in rounding or conversion rates. This could cause a suboptimal solution to be found. Additionally, the tedious process means that more research has to be conducted and errors could be introduced in multiple locations.

## 8.2 Conclusion

Our model is used to simulate the correlation between the number of tourists with the sustainability of the city's tourism industry. By utilizing multiple numbers and variables, our model can be readapted to tourist attractions beyond the city of Juneau. In addition, with the factors we set, our model accounts for the numerous aspects of sustainability within the tourism industry, both for the environment and society.

However, it's also important to note the weaknesses of our model. Our model asks for lots of data for greater precision that, at some times, may not be easily available to be found. Moreover, our model asks for a lot of unit conversions and rounding, enabling a significant amount of room for error.

Regardless, our model is robust with increased precision that can help city governments determine and improve the sustainability of their tourism industry. Although there may be weaknesses and errors, our model can substantially help tourist attractions in promoting greater sustainability measures and improving the world's future, one city at a time.

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