

## Guarding Our Prized Possessions in the Midst of a Violent Storm

### Summary

In recent years, the global climate has been experiencing widespread anomalies, which have caused severe losses to property owners and posed great challenges for insurance companies. To address this issue, we have developed an **insurance decision model** and a **building evaluation model** to help insurance companies find a balance for long-term development, and community managers better go respectively and protect their precious properties.

For **Model I**, We categorize extreme weather events into 3 representative categories: **floods, winds and fires**. For floods and windstorms, we introduce a threshold parameter  $\theta=10\%$  and build a **linear model** to judge the extreme weather conditions based on the precipitation, average wind speed and gust wind speed of a region in previous years. For fire, we use the **FFDI** model (for which the drying factor **DF(0-10)** is simulated) and its fixed rating scale for judgment. We also introduce an **index model** of premiums  $p$  and the number of policies signed  $I$  to analyze two dimensions in the interest decisions of insurance companies. Finally, we modeled in **Houston, North America** and **São Paulo, South America**.

For **Model II**, we modeled the proportion  $R$  of average loss from extreme events that occupies the average income through regional extreme climate prediction based on the predicted results of **Model I**, where the single loss amount is assumed to be distributed according to **Pareto**. Then, based on the **ALARP** criterion, we define **climate risk index  $\omega$**  by combining the predicted proportion with the income index and the regional population density, and apply  $\omega$  to three selected cities, Huston, St Louis, and Reno, and analyze each of them comprehensively by combining the results of **Model I**.

For **Model III**, we focuses on the indicators of historical value, scientific and technological value, economic value, artistic value and environmental value. The evaluation process adopts the expert scoring method, and the weights of the evaluation indicators are determined through the hierarchical analysis method (**AHP**), **entropy weight method**, and **structural equation modeling method**. At the same time, **Kmeans** cluster analysis was applied to classify the buildings according to their conservation significance. Based on the results, recommendations were made for the measures to be taken by community leaders to conserve the buildings in the community.

In the end, we chose the **St. Louis Cathedral**, a historic landmark, to evaluate based on our proposed model and, based on the results, wrote a one-page letter to the Mayor of the City of St. Louis recommending a plan, timeline, and cost proposal for the future of their treasured landmark.

**Keywords:** property insurance; extreme weather; ALARP; AHP; Kmeans

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## 1 Introduction

### 1.1 Background

Over the past decades, human activity has released gases that trap more heat than in the past, leading to warmer temperatures, melting glaciers and rising sea levels, with extreme weather becoming more frequent. According to [1], the astronomical 250% increase in insured losses from extreme weather events over the past 30 years represents a significant challenge for the insurance industry. As extreme weather events become more common, insurers will face increasing losses. Insurer profitability and homeowner affordability are in crisis in response to climate change, and insurers must find new ways to balance risk and reward.



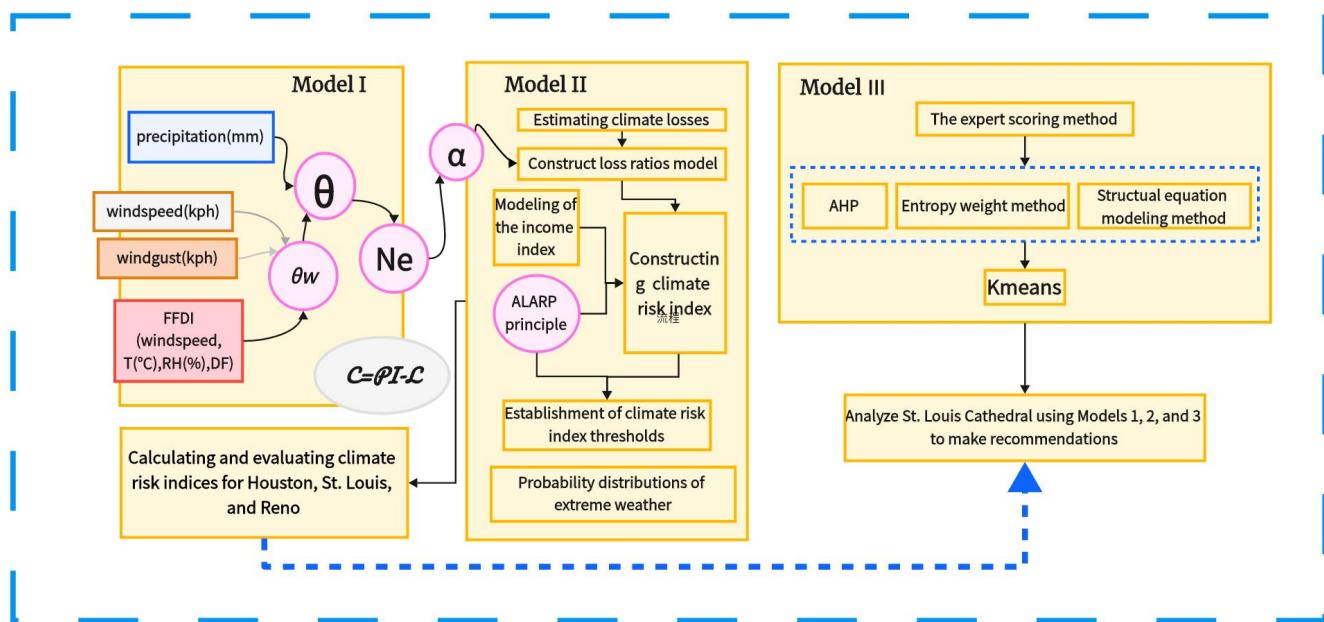
**Figure 1.** Disasters caused by extreme weather

### 1.2 Restatement of the Problem

- Develop a model to help insurance companies analyze **1)conditions for underwriting, 2)claims thresholds, and 3)property owner behaviors that may influence decision-making** to help insurers determine whether they should underwrite policies in areas with increased numbers of extreme weather events. **Demonstrate** the application of the model on two regions on different continents.
- Adjust the insurance model to evaluate **1)the likelihood** of building on certain sites, **2)specific locations, and 3)construction measures** for communities and real estate developers.
- Develop a preservation model for community leaders to help **1)identify buildings** that should be preserved because of their cultural, historical, economic, or community significance and **2)determine appropriate preservation measures**.
- Apply the insurance and preservation models developed above to **assess the value** of a historic landmark that would experience extreme weather events. Based on the results of the modeling assessment, write a **one-page letter** to the community providing them with

a future preservation plan, timeline, and cost proposal for the landmark.

### 1.3 Our Work



**Figure 2.** Our Work

## 2 Assumptions

- **Assumption 1:** All property insurance policies do not differ in terms of policy and contain only three types of extreme weather: flood, wind and fire (for reasons explained in 4.1).
- **Assumption 2:** Insurance companies have an unlimited amount of costly capital and labor reserves without regard to their size.
- **Assumption 3:** The real estate development market is positively correlated with the economy.
- **Assumption 4:** All buildings have direct or indirect benefits.

## 3 Notations

The primary notations used in this paper are listed in Table 1. Local variables will be explained in the text.

Symbol	Description	unit
$\theta$	cut-off points for judging extreme events in linear models (0-1)	%
$C_{VAL}$	cut-off values for $VAL$ data ( $VAL$ is one of the meteorological data)	specific
$N_e$	number of Extreme Events Judged for $VAL$ Weather Type in a Year	count

$I_0$	=1,308,966.798, constant, the average of the number of policies issued in a state during a one-year period	House-Years
$p_0$	=1,411, constant, the average of premiums across the United States during a one-year period	\$/House-Years
$C$	Amount of benefit expected from the insurance company in one year	\$
$L$	Expected amount of compensation from the insurance company within one year	\$
$(P, C)_{best}$	The average value of one year's optimal premium take and its corresponding amount of the insurer's expected profit according to equation (9)	(\$, \$)
$\lambda$	Probability of a claim event occurring within one year obtained by modeling according to equation (11)	%
$\omega$	Extreme Climate Risk Index	/
$R$	The economic losses from extreme weather in the region are more than	%

**Table 1.** Notations

## 4 Model I: Property Insurance Decision Model

### 4.1 Problem analysis and data collection

Property insurance provides financial reimbursement to the owner or renter of a structure and its contents in case there is damage or theft. Property insurance can include a number of policies, such as homeowners insurance, renters insurance, flood insurance, and earthquake insurance[1]. In order for a region to focus on the relationship between its extreme weather events and insurance risk assessment, this paper 1)does not take non-catastrophe factors( $\leq 8\%$ ), such as theft, into account, and 2)does not make specific distinctions between types of insurance or policies, uniformly **treating all extreme weather insurance types as property insurance**.

Cause of Loss	Average Ratio(%)
Wind and hail	43.71
Fire and lightning	23.58
Water damage and freezing	24.71
All other property damages	8.00
Total	100

**Table 2.** Property Damage Insurance Losses By Cause, 2017-2021[2]

Based on the statistics in [2], we calculated how much of the overall property insurance type is accounted for by various weather insurance types between 2017 and 2021(Table 2). To further simplify the model and focus on the main factors, we divided extreme weather events into three categories: **high winds, wildfires, and floods**, after excluding events that cannot be

accurately quantified and have a smaller impact (hail, freezes, and lightning).

More than one-third of respondents in the Pacific (36%), the Midwest and South Central (34%), and the Mid-Atlantic (33%) reported challenges obtaining or renewing homeowner's insurance due to natural disasters[3]. So we chose representative states from these three regions (**California, Arkansas, and New Jersey**) for the Extreme Weather Threshold Review. We collected all weather data(.csv) for these 3 states in [4] for the years 2017-2021, spanning 5 years and totaling 5,476 pieces of data.

## 4.2 Determining Parameters - Extreme Weather Event Judgment Thresholds

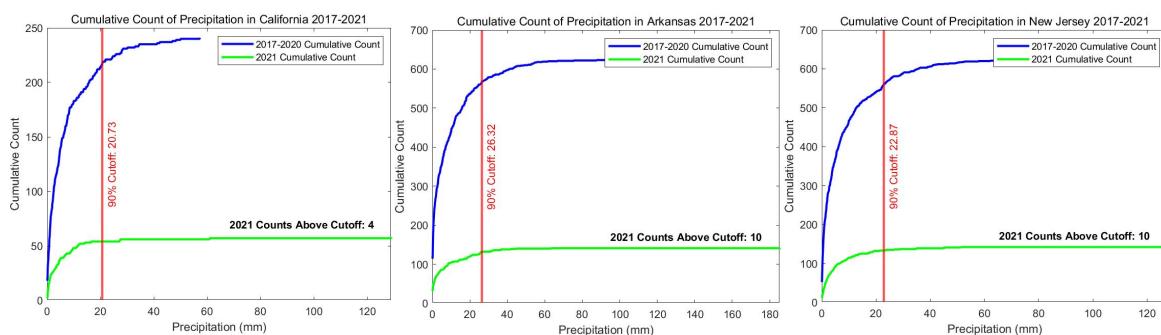
### 4.2.1 Excess Rainfall (Potential Flood Hazards)

Excess rainfall was identified when the daily rainfall exceeded the 90th percentile of a grid's non-zero values over the period of study[5]. Based on this already applied statistical method, we adopt  $\theta_F = 10\%$  as the original cut-off parameter for flood judgment.

$$\left\{ \begin{array}{l} \text{Ordered list : } \{VAL_{(1)}, VAL_{(2)}, \dots, VAL_{(N)} | VAL_{(i)} \leq VAL_{(j)}, 1 \leq i \leq j \leq N\} \\ \text{Cut-off Value : } C_{VAL} = Q(1 - \theta) = \min\{x | P(X \leq x) \geq 1 - \theta\} \\ = VAL_{[N \times (1-\theta)]} \end{array} \right. \quad (1)$$

According to (1), using the precipitation data from 2017-2020 (excluding the 0 value for non-rainfall weather), we can preliminarily derive the critical value  $C_p$  for judging the extreme rainfall weather events.  $VAL$  is the amount of **precipitation(mm)** in a day in the region,  $N$  is the number of data days involved in calculating the critical value, and  $\theta$  is the parameter that we can make adjustments. Further, we calculated the number of extreme rainfall events in 2021 based on (2), as shown below.

$$\begin{aligned} N_e &= \sum_{i=1}^N I, \quad V = \{VAL_{(1)}, VAL_{(2)}, \dots, VAL_{(N)}\} \\ I &= \begin{cases} 1, & VAL_{(i)} \geq C_{VAL} \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (2)$$



**Figure 3-5.** Cumulative Count of Precipitation for 3 states (2017-2020, 2021) with cut-off values(mm) and excess rainfall event counts (California[20.73, 4], Arkansas[26.32, 10], New Jersey[22.87, 10],  $\theta=10\%$ ).

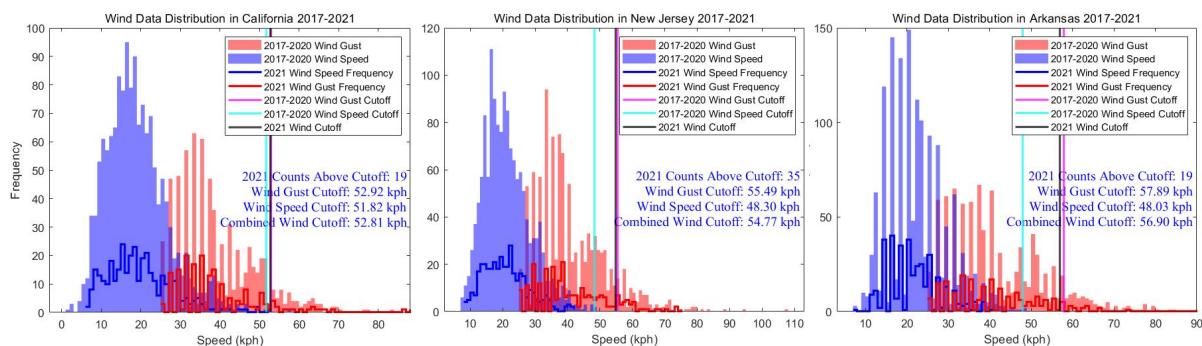
### 4.2.2 High Winds (Hurricane Damage)

We have two factors to consider for calculating high wind extremes: **1)windspeed(kph)**, the wind speed in days, which is the maximum value per hour of the day (measured at 10 meters above the ground with no nearby obstructions). **2)windgust(kph)**, the maximum wind

speed measured over a short period of time (usually less than 20 seconds), which is significantly higher than the average wind speed (usually wind speeds greater than 8 kph). Based on the single-factor bounds formula of (1), we added a **weighting calculation** to synthesize the effects of wind speed.

$$C_w = \mathbf{w}^\top \mathbf{x} + b, \quad \mathbf{w} = \begin{bmatrix} \theta \\ 1 - \theta \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} C_{ws} \\ C_{wg} \end{bmatrix} \quad (3)$$

In (3) for the calculation of the bound  $C_w$  for windy weather, the initial value  $\theta_w$  of is also set to **10%**.  $C_{ws}$  and  $C_{wg}$  are the one-factor bounds for windspeed and windgust, respectively, derived based on (1) using the parameters  $\theta_{ws} = 0.1\%$  and  $\theta_{wg} = 10\%$ . Since our reference is the realistic past data for the area, the value of  $b$  is set to 0 here without any further increase. Combining (1)(2)(3), we use the regional windspeed data from 2017-2020 compared to the cutoff values to calculate the number of extreme wind events in the region in 2021, as shown below. Obviously, gusts will be taken more into account in the calculation of the wind hazard thresholds, but the comparison with them will still be the wind speeds across the region.



**Figure 6-8.** Distribution of Wind(kph) with Cutoff Points for 3 states (2017-2020, 2021) California[52.81, 19], Arkansas[54.77, 35], New Jersey[56.90, 19],  $\theta_{ws} = 0.1\%$  and  $\theta_{wg} = 10\%$ .

#### 4.2.3 Wildfires (Danger of Burning Houses)

The FFDI(Forest Fire Danger Index) is a key tool for assessing fire danger in Australia. The formulation of the **FFDI** (e.g. Noble et al 1980) is based on the temperature ( $^{\circ}\text{C}$ ),  $T$ , wind speed (kph),  $v$ , relative humidity (%),  $RH$ , and a component representing fuel availability called the Drought Factor,  $DF$ [6], as shown in equation(4).

$$FFDI = 2e^{(-0.45+0.987+\ln(DF)-0.0345RH+0.0338T+0.0234v)} \quad (4)$$

The Drought Factor is given as a number between 0 and 10 and represents the influence of recent temperatures and rainfall events on fuel availability (see Griffiths 1998 for details)[6]. Since the calculation of DF involves vegetation at a specific geographic location, it is simplified in this paper and simulated using the previously mentioned precipitation. The simulated DF factor calculation is shown in (5).

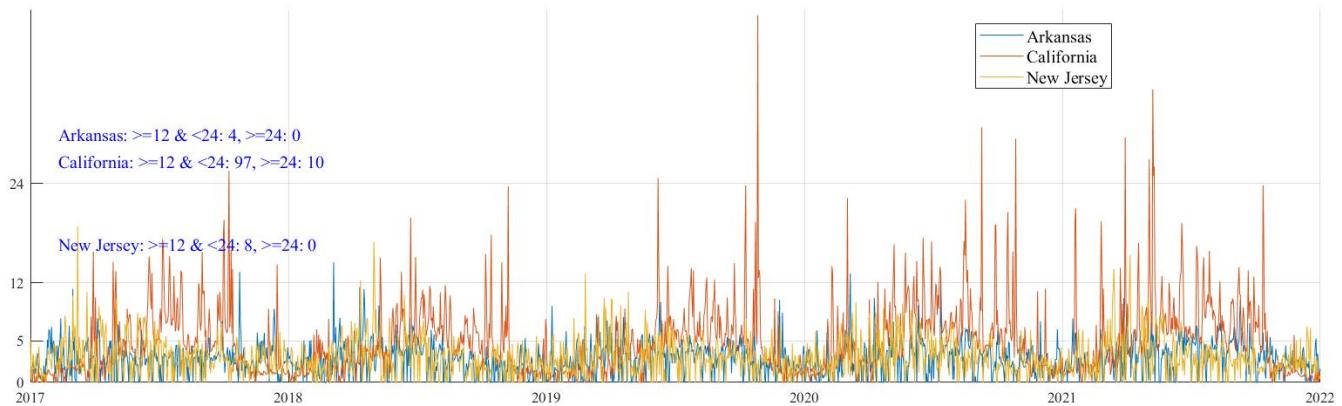
$$DF = \max \left\{ 10 \times \left( 1 - \frac{VAL_{precip}}{C_p} \right), 0 \right\} \quad (5)$$

We obtain a proportional value based on precipitation(mm) in a day and the critical value calculated in (1). We chose to use the **inverse ratio** to represent the dryness of a day in a region as a function of rainfall (excluding the case where a region experiences both floods and fires). Since DF takes values in the range [0,10], we multiplied the ratio by a factor of 10 to obtain a value close to the one applied in Eq. (4).

Fire Danger Rating	FFDI Range
Low	0-5
Moderate	5-12
High	12-24
Very High	24-50
Extreme	50+

**Table 3.** FFDI values for each fire danger rating class (Luke and McArthur 1986)[6]

Based on the above, we have the following four dimensions of data: 1) **drying factor DF** obtained from precipitation (mm) introduced in 4.2.1, 2) **windspeed (kph)** introduced in 4.2.2., 3) the average daily **temperature T (°C)**, 4) **the relative humidity RH(%)**, which is the amount of water vapor present in the air compared to the maximum amount of water vapor that could be present at a given temperature. Using (4)(5) to calculate the FFDI value for a day in an area and referring to the fire risk categorization data in Table 3, this paper concludes that when the FFDI value for a day **exceeds 12**, an extreme fire event has occurred in that area. Based on the above data for a region for the years 2017-2021, we calculated the number of days of fire in the three states during the five-year period as follows.



**Figure 9.** Schematic of FFDI values and number of extreme fires in 3 states(2017-2021) (California[97, 10], Arkansas[4, 0], New Jersey[8, 0],  $C=[12, 24]$ ).

#### 4.3 When, or Not to Take Risks (Profits of Insurance Companies)

For the amount of financial compensation for property after an extreme weather event, this paper takes the statistical value in [2], which is **the cost of claims incurred for one house per year(House-Years)**. Combined with the assumptions in 4.1, this paper will use the corresponding values in Table 4 as the

base values  $L$  for the compensation amount before considering the degree of loss.

Cause of Loss	Average Raio(%)	Claim Severity(\$)
Water damage and freezing	26.86	12,514
Wind and hail	47.51	12,913
Fire and lightning	25.63	83,519

**Table 4.** Property Damage Insurance Losses (Average), 2017-2021[2]

According to [7], this paper sets the following average criteria for calculating the profitability of insurance companies: **1)Market average level premium  $p_0 = 1,411$  (\$/H-Yrs, 2021)**, which is the average of premiums across the United States (regardless of tenant type). **2)Market average number of policies  $I_0$  issued = 1,308,966.798 (H-Yrs)** (the average of the number of policies issued in a state during a one-year period).

This paper specifies the **basic formula** for calculating the amount of profitability of an insurance company as shown in (6). Where  $C$  represents the profit for one year (\$),  $p$  represents the cost of signing up a home for one year of insurance (\$/H-Yrs),  $I$  represents the number of policies signed up by customers in one year (H-Yrs), and  $L$  represents the total amount of claims made by customers in one year.

$$C = p \cdot I - L \quad (6)$$

Based on (2) in 4.2, **1)θ is the definition of the condition by insurance companies** (not surprisingly,  $\theta$  is positively correlated with the number of extreme weather events), we can derive the number of days in a year for each extreme weather event  $N_e$  ( $N = 365$ ). In (7) for the calculation of the compensation amount for a year  $L($)$ , the ratio of  $N_e$  to  $N$  simulates the proportion of houses affected by extreme weather and the total number of houses in a year  $I_0$  is the number of houses damaged in a year (H-Yrs),  $T$  is the type of the extreme weather event ( $T = 3$ ), and according to Table 4,  $L_t$  is the amount claimed corresponding to this type of weather.  $\beta$  is a random value generated from a normal distribution with  $\mu = 1.0$  and  $\sigma = 0.01$  (representing the severity of the loss event).

$$L = \beta \cdot I_0 \sum_{t=1}^T \frac{N_e}{N} L_t \quad (7)$$

We use **2)the  $p$  ratio**, which is the ratio of the difference between the insurer's pricing and the average market price as a percentage of the average market price, **as a second factor that affects the insurer's decision**. It affects the insurer's expectation of the value of policies signed by customers.

$$I(p) = I_0 e^{-\frac{p-p_0}{\tau p_0}} \quad (8)$$

In (8),  $I$  is the number of policies issued(H-Yrs),  $p$  is the premium pricing,  $p_0$

is the average market price, and  $\tau$  is a custom parameter to indicate the relationship between an increase in the  $p$  percentage and a decrease in the predicted number of policies issued. Here,  $\tau = 0.45$  is chosen according to [8]. Combining (6)(7)(8), we can obtain the following formula(8) for exponential benefits with  $\theta$  and  $p$  as independent variables.

$$C = (pe^{-\frac{p-p_0}{\tau p_0}} - \beta \sum_{t=1}^T \frac{N_e}{N} L_t) \cdot I_0 \quad (9)$$

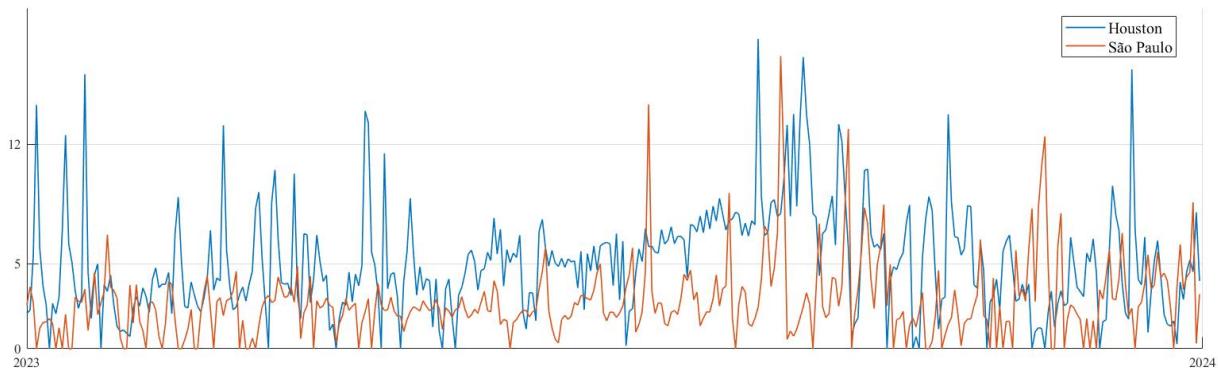
The insurer's decision-making process: 1)Determine the initial value of the claim condition  $\theta$ , which is the parameter that directly affects the number of extreme weather events  $N_e$ . 2)Based on (7), derive the expected amount of claims for a year in the region  $L$ . 3) Determine the insurer's profitability target  $C$  for a year, and **analyze the relationship between the benefit  $C$  and the premium  $p$**  according to (9) to make the final decision: increase  $p$  to meet the expectation? Return to 1) Adjust  $\theta$  to improve profit margin? It is worth noting that  $\theta$ , as a judgment parameter for extreme weather, must not be so outrageous that it reduces the owner's willingness to sign up (even though it is not involved in the arithmetic in this model).

#### 4.4 Demonstration on Two Different Continental Areas

In this paper, two regions, **Houston, located in North America**, and **São Paulo, located in South America**, have been selected for the demonstration of the above model. Based on the data sources in 4.1 (2019-2022) and following the parameter  $\theta$  settings in 4.2, the counts of extreme weather events for 2023 for both regions are shown below.

Extreme Weather Event	Houston	São Paulo
Excess Rainfall	3	11
High Winds	47	20
Wildfires	14	4

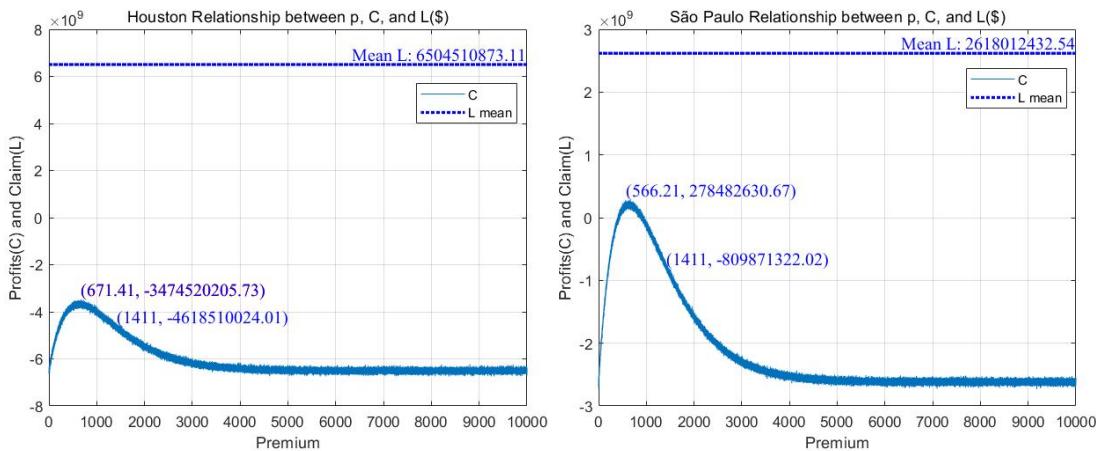
**Table 5.** Counts of extreme weather events in two regions for 2023



**Figure 10.** Schematic of FFDI values per day in 2023 for the two regions

Figure 11-12 shows the relationship between the amount of insurance  $C$  and the premium  $p$  for the two locations, as well as the average amount of compensation  $L$ . It is clear

that 1)for Houston, it is not profitable even if the highest point of the function  $(P,C)_\text{best}$  is taken; at the same time, its claims in a year amount to almost triple the amount of São Paulo's. In short, it is not a suitable place for the insurer to grow in the long term. 2)for São Paulo , it can be seen that it is possible to realize profitability (even if it is not high for the whole) in a certain range of premium take-offs, while there is a rather high cost (related to the size of the insurance company). It is suggested that the insurance company can adjust the parameters  $\theta$  appropriately to realize more extreme weather events determination.

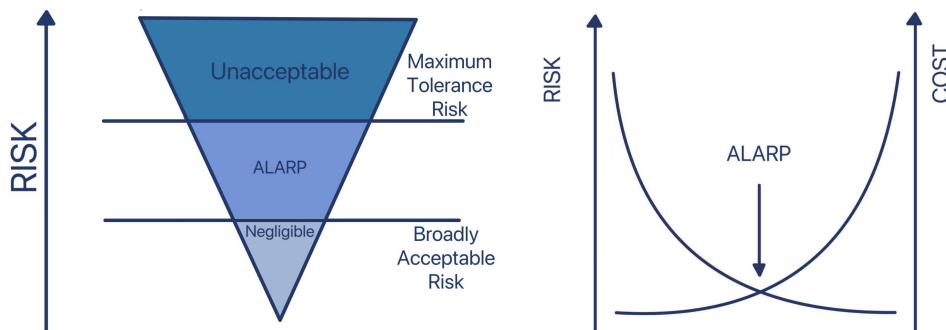


**Figure 11-12. (Houston**[(671, -3,474,520,205.73), 6,504,510,873.11],  
**São Paulo**[(566.21, 278,482,630.67), 2,618,012,432.54])

## 5 Model II: Model for property construction

### 5.1 ALARP

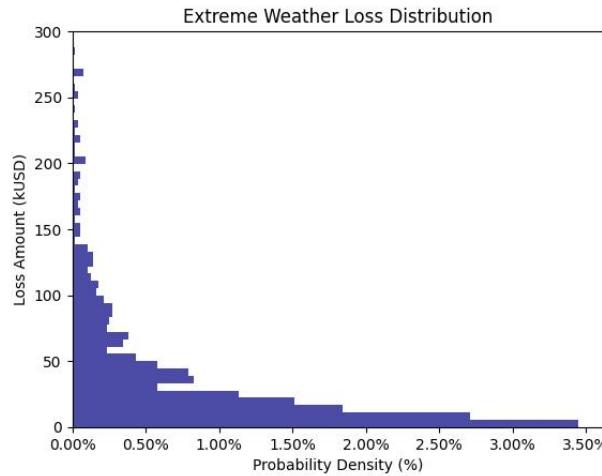
ALARP, or as low as reasonably practicable, is a risk management principle used primarily to assess and control potential hazards and risks according to [12]. This principle emphasizes the reduction of risk to the lowest possible level within acceptable limits, taking into account feasibility and cost-effectiveness, and finding a balance between risk and costs as illustrated in Figure 13. As is shown in Figure 14, project risks are categorized into Unacceptable Zone, ALARP Zone, and Negligible Zone by the different risk criteria.



**Figure 13-14.** Schematic definition of ALARP

## 5.2 Quantify Losses Due to Extreme Climate

The distribution of losses due to extreme weather events of different degrees is simulated using the Pareto distribution. In this way the sequence of losses caused by extreme weather can be simulated. Combined with the characteristics of real events, the sequence of losses obtained by the Pareto distribution assumption after several tests with scale parameter 50 and shape parameter 2 is shown in Figure 15.



**Figure 15.** Pareto-simulated distribution of loss amounts

However, it can be seen through the calculation in **Model I** that there exists a portion of the losses against property damage caused by extreme weather that can be offset by the insurance company's premiums .Hence, we further utilize the weather data to derive the insurance purchase quantity  $Num$  and the insurance company's payout threshold  $\alpha$  to simulate the number of losses  $\alpha Num$  based on **Model I**. Combined with the average insurance price  $L$ , we derive the total loss sharing ratio  $R$  by using formula(10).

$$R\bar{E} = Num \left( \frac{\alpha b}{(b - 1)} - L \right) \quad (10)$$

In the equation  $b$  refers to the shape parameter of Pareto and  $\bar{E}$  denotes the average income of the area, and the value of  $\alpha$  is calculated from **Model I** ( $N=365$ ) as shown in formula (11).

$$\alpha = \frac{N_e}{N} \quad (11)$$

## 5.3 Climate Risk Index

The resilience of the system, i.e. the ability to maintain essentially the same function, structure, feedbacks and identity while experiencing shocks, is gradually increased by the impact of climate on the system as the number of weather extremes increases. It is assumed that the impact of climate on a region is fully captured by the economic losses caused by weather extremes as well as the local population density, and it is assumed that the size of the regional real estate market is fully captured by the income level and the population density, due to the fact that while technology and history may have an impact on real estate

development, this is also reflected in the level of local incomes. Therefore, this paper combines ALARP to construct a climate risk index,  $\omega$ , for the level of sustainable economic development, and uses this index to determine the risk faced by real estate developers when building communities in a certain area.

In this paper, we use the results of the prediction of the number of insurance claims in **Model I** to calculate the difference between losses and premiums, and use the formula (10) to obtain the percentage  $R$  of this difference to the average income of the region, and then use the relationship between the level of local income and the level of income in the region to obtain the income index  $e$ . Taking into account the impacts caused by the population density of the region on the sustainability of the community, we obtain the climate risk index,  $\omega$ , of the development carried out by the real estate developer.

$$\omega = \frac{\tilde{e}\rho}{\tilde{R}} \quad (12)$$

where  $\tilde{e}$  and  $\tilde{R}$  refer to the regularized data and  $\rho$  refers to the population density index of the area.

## 5.4 Results

Combining the risk assessment criteria ALARP and the climate risk index  $\omega$ , we obtain the following risk assessment criteria.

$$\omega = \begin{cases} > 3.4 & \text{Negligible Risk} \\ 1.3 \sim 3.4 & \text{Acceptable Risk} \\ 0 \sim 1.3 & \text{Unacceptable Risk} \end{cases} \quad (13)$$

Developers can determine whether an area is suitable for a community based on the climate risk index  $\omega$  of the site. Next, we selected weather and income data for Huston, St. Louis, and Reno to model using this model. The results are shown in Figure16.

Houston	St.Louis	Reno
<ul style="list-style-type: none"> <li><math>\omega=1.799</math> Acceptable Risk</li> <li>Risks are relatively high, with a dry climate, mainly wind and fire.</li> <li>Higher economic level, within the acceptable risk range for real estate development companies.</li> </ul>	<ul style="list-style-type: none"> <li><math>\omega=1.636</math> Acceptable Risk</li> <li>Some probability of risk, relatively wet, with some risk of hurricane climate</li> <li>Average economy, within acceptable risk range for real estate development companies</li> </ul>	<ul style="list-style-type: none"> <li><math>\omega=0.156</math> Unacceptable Risk</li> <li>Extremely high risk of emergence, dry climate, high probability of fire climate.</li> <li>The economy is average and in the range of unacceptable risk for real estate development companies.</li> </ul>

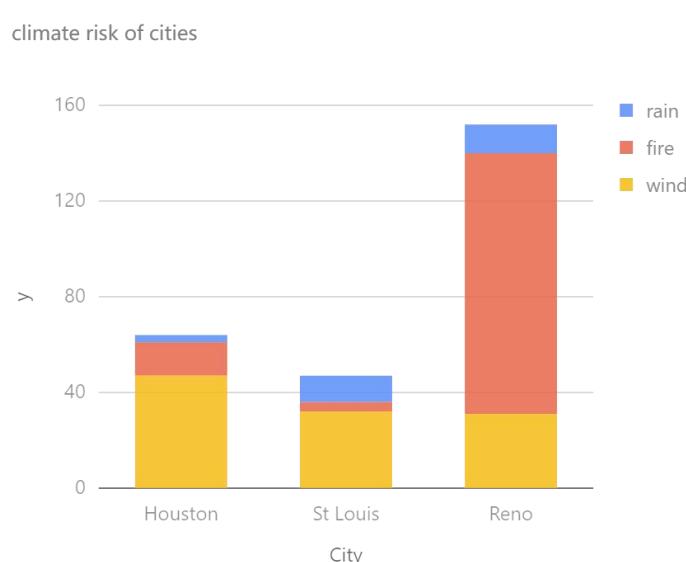
**Figure 16.** Risk and assessment results of three cities

In addition, as is shown in Figure17, we have analyzed each of the three cities using the **Model I** to describe the climate risk, and for the sake of community resilience and sustainability, we have made the following recommendations for development in the different areas.

- **Building resilient communities.** According to the climate characteristics of different

regions, use special structural designs to ensure that houses can withstand extreme weather events such as storms, earthquakes and floods. Develop community-level extreme weather response plans, including evacuation routes, emergency shelters, and communication systems, to improve community response capabilities in the event of disasters.

- **Mitigate climate change.** Focus on environmental sustainability in community building, adopt environmentally friendly materials and technologies, promote low-carbon, high-efficiency building design, and incorporate consideration of green fuels, water resource management, and green land planning in construction.
- **Green economic development.** Turning climate change into new opportunities for economic development and economic diversification through the creation and promotion of green jobs.



**Figure 17.** Distribution of extreme weather risk scores for cities

## 6 Model III: Model for Evaluation of Buildings

The value of a building consists of two parts: the overall value and the sub-value. The overall value is influenced by the sub-value, and both the overall value and the sub-value can be quantified and assessed. The subvalues include historical value, scientific and technological value, economic value, art value and environmental value, which are quantified and summarized by indicators, and the basic model can be expressed as follows[10]:

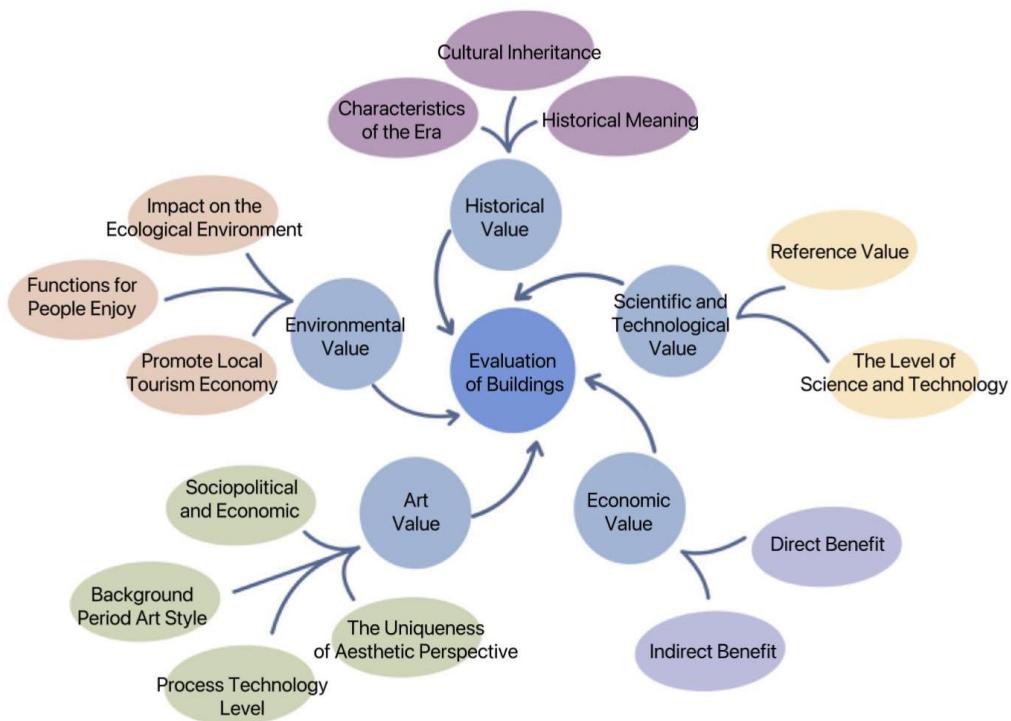
$$y = \sum_{i=1}^5 a_i x_i \quad (14)$$

$x_1, \dots, x_5$  denote the five indicators just mentioned, such as historical value, scientific and technological value, etc., respectively, and  $a_1, \dots, a_5$  are the weight coefficients corresponding to each indicator, with the overall value being  $y$ .

## 6.1 Determination of evaluation indicator scores

### **6.1.1 Basis for assessing indicators**

Historical value [11] is based on the depth and breadth of the human, social, environmental and historical memory embodied in the building and the extent to which it contributes to cultural heritage and historical significance. Scientific and technological value is based on the level of science and technology of the building's own time as reflected in the building, as well as its value for scientific and technological research. Economic value is based on the valuation of the building's direct and indirect income obtained through the income approach. Art value is based on the uniqueness of the socio-political and economic context, the artistic style of the era, the level of craftsmanship and technology, and the aesthetic perspective reflected in the building, as well as its contribution to the art and culture of successive generations. Environmental value is based on the characteristics of the building as part of the ecological environment, including its impact on the ecological environment and its function for human enjoyment and pleasure.



### **Figure 18.** Basis for assessing indicators

### 6.1.2 LLM-Based Simulation Expert Scoring Method

Due to the limitation of conditions, we determine the score of each assessment index of the building based on the traditional expert scoring method, combined with the above assessment indexes, through the simulation expert scoring method based on the large language model. The big language models used in this are **bard-feb-2024**, **gpt-4-0125-preview**, **gpt-3.5-turbo-0125**, **gemini-pro-dev-api**, and **mistral-medium**, and the score value of each

assessment index is divided into 0-10 points. A concrete example is shown below, which is an evaluation of Halgrims Cathedral in Iceland by five simulation experts, with five evaluation metrics in total, and the evaluation scores as shown in Table7.

LLM	Historical Value	Scientific and Technological Value	Economic Value	Art Value	Environmental Value
bard-feb-2024	8	7	9	9	8
gpt-4-1106-preview	8	7	6	9	8
gpt-3.5-turbo-0125	8	6	7	9	7
gemini-pro-dev-api	9	8	9	10	9
mistral-medium	8	7	8	9	8

**Table 7.** Evaluation scores for Halgrims Cathedral by 5 simulation experts (0-10)

## 6.2 Determination of assessment indicator weights

In this study, three different methods will be used for the determination of the weights of the assessment indicators, and finally the most ideal method will be selected as the weight confirmation method for this model, and in this section, the data in Table 7 will be used as a sample for the demonstration of the method.

### 6.2.1 AHP-Based Determination

Hierarchical analysis, or AHP for short, was proposed in the early 1970s by T.L. Saaty. Hierarchical analysis is a decision-making method that combines qualitative and quantitative analysis based on the decomposition of decision-making elements into multiple levels, such as objectives, criteria, and scenarios. In this study the hierarchical structure is divided into two levels, i.e. target layer and indicator layer. The overall value of the building y is the target layer, and five indicator layers are set for historical value ,scientific and technological value, economic value, artistic value and environmental value.

#### 1. Construct judgment matrix

Constructing a judgment matrix is to compare the elements with each other two by two, and to determine the weight of each criterion on the target level. In order to transform the expert scores into a judgment matrix, it is necessary to use a method to compare the relative importance between indicators. In this study Santy's scale of 1 to 9 was used to describe the relative importance between two indicators.

Scale	Meaning
1	Represents that both elements are of equal importance when compared.

3	Indicates that the former element is slightly more important than the latter when compared.
5	Denotes that the former element is significantly more important than the latter when compared.
7	Signifies that the former element is extremely more important than the latter when compared.
9	Indicates that the former element is strongly more important than the latter when compared.
2, 4, 6, 8	Represents the intermediate values between the adjacent judgments mentioned above.
Reciprocal of 1~9	Indicates the importance of comparing the two factors in reverse order.

**Table8.** Santy's 1-9 Scaling Methods

If an expert considers indicator  $i$  to be  $k$  times more important relative to indicator  $j$  than indicator  $j$  is relative to indicator  $i$ , we determine the judgment matrix based on this relationship. After obtaining the  $1/a_{ij}$  judgment matrices of all the experts, they can be averaged to obtain a combined judgment matrix. This combined judgment matrix can be used for further calculations of the hierarchical analysis method, such as calculating weights and consistency indicators.

y	$x_1$	$x_2$	$x_3$	$x_4$	$x_5$
$x_1$	1	7/8	9/8	1	1
$x_2$	8/7	1	1	9/8	8/7
$x_3$	8/9	1	1	1	7/8
$x_4$	1	8/9	1	1	1
$x_5$	1	7/8	8/7	1	1

**Table9.** Halgrims Cathedral Judgment Matrix

## 2. Hierarchical single ranking and consistency test

In hierarchical single ranking, the eigenvectors of the judgment matrix need to be computed and then normalized to obtain the weights of each indicator.

(1)Based on the maximum eigenvalue  $\lambda_{max}$  and the order  $n$  of the judgment matrix, calculate the consistency index ( $CI$ ) according to formula(14).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (15)$$

(2)According to the order of the matrix check the following Table10 to obtain the random consistency index( $RI$ ).

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.44	1.45	1.49

**Table10.** RI Value Reference Table

(3) Calculate Consistency Ratio(CR)

$$CR = \frac{CI}{RI} \quad (16)$$

(4) If the consistency ratio  $CR$  is less than a reasonable threshold (usually 0.1), the judgment matrix is considered to be reasonably consistent; otherwise, it is necessary to reconsider the expert's evaluation or adjust the judgment matrix.

Symbol	Value
$a_1$	0.199
$a_2$	0.216
$a_3$	0.190
$a_4$	0.195
$a_5$	0.200
$CI$	0.001
$CR$	0.002

**Table11.** Results of Hierarchical Single Ordering and Consistency Tests

### 3. Result

Based on the weighting coefficients obtained from the hierarchical analysis method, we get the overall value of Halgrims Cathedral  $y = (8.169, 7.599, 7.373, 8.979, 7.979)$ , and further calculate the overall value  $y = 8.020$ .

#### 6.2.2 Entropy Weight Method

The use of entropy method for the determination of weights of multiple indicators is a common method, which is based on the concept of entropy in information theory and uses the degree of dispersion of the data of each indicator to calculate the weights.

##### 1. Data standardization:

The purpose of data standardization is to map the data to the same scale in order to eliminate the differences in magnitude and scale between different indicators. However, since the simulation experts score each indicator in the same division range (0-10), no further data standardization is required.

##### 2. Calculate the weights of the indicators:

For each indicator, calculate its information entropy, the larger the information entropy indicates the higher the degree of discrete data, i.e., the smaller the corresponding weights. The formula for calculating the weights is

(  $H_i$  denotes the information entropy of indicator i):

$$W_i = \frac{1 - H_i}{\sum_{i=1}^n (1 - H_i)} \quad (17)$$

##### 3. Weight Normalization:

The obtained weights are normalized to ensure that all weights sum to 1.

Insex	Information Entropy	Weights
$x_1$	5.026	0.189
$x_2$	7.667	0.314
$x_3$	5.743	0.223
$x_4$	2.357	0.064
$x_5$	5.468	0.210

**Table12.** Halgrims Cathedral Entropy Method Indicator Weights Calculation Results

#### 4. Result

The overall value of Halgrims Cathedral  $y = (7.973, 7.304, 7.003, 8.750, 7.750)$  was obtained from the weighting coefficients obtained from the entropy method, and the overall value  $y = 7.756$  was further calculated.

#### 6.2.3 Structural Equation Modeling Decomposed Into Basic Modules

In this study there are 5 assessment  $x_1, \dots, x_5$  metrics, For each metric there are 5 simulation experts who gave assessment scores, i.e., each  $x_i$  is an N-dimensional column vector, so there is a  $5 \times 5$  data matrix, i.e., 5 rows and 5 columns.

Let the original observed data matrix  $X' = (x'_1, \dots, x'_5)$  and the unknown vector  $B' = (b'_1, \dots, b'_5)$  then the relationship between  $y$  and  $x$  can be approximated as:

$$X \approx By \quad (18)$$

Transposing both sides of the above equation and multiplying them separately gives  $XX' = Byy'B'$ , assuming  $y$  is a unit vector, i.e.,  $yy' = 1$ , which gives:

$$XX' = BB' \quad (19)$$

Use the vector  $B'$  to go left multiply both sides of (18) to get  $B'X \approx B'By$ . Thus  $y$  can be computed, and writing the component form is:

$$Cy_j = (b_1x_{1j} + \dots + b_5x_{5j}), j = 1, 2, \dots, 5, C = B'B = b_1^2 + \dots + b_5^2 \quad (20)$$

Thus we have obtained an estimate of  $y$  using least squares with the modulus length constrained to be a unit vector ( $yy' = 1$ ), then we can use ordinary multiple linear regression to estimate the weight coefficients  $a_1, \dots, a_5$  using ordinary multiple linear regression for formula(1). Currently, we need to add new constraints in place of the modulus length unit vector constraints:

$$a_1 + \dots + a_5 = 1, a_1, \dots, a_5 \geq 0 \quad (21)$$

Using the known  $5 \times 5$  dimensional observation matrix  $X$ , one can compute its covariance matrix  $XX'$ , take out its main diagonal elements as  $d_1^2, \dots, d_5^2$ , make  $D = d_1^2 + \dots + d_5^2$  and compute the vector  $E = (d_1/D, \dots, d_5/D)$  which is the coefficients in formula(14). Calculate the sum

of the components of  $E$ . Use this sum to normalize the vector  $E$ , which is the desired weight coefficient that satisfies the conditions of the formulation.

Insex	$x_1$	$x_2$	$x_3$	$x_4$	$x_5$
Weight	0.1628	0.3023	0.3023	0.1163	0.1163

**Table13.** Results of the Calculation of the Weights of the Indicators of Hargrims Cathedral

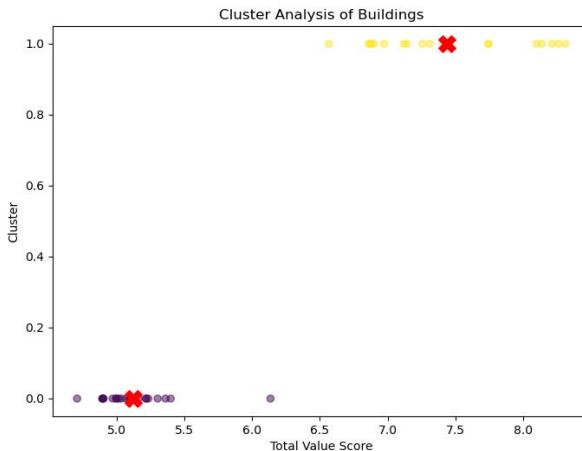
Based on the weighting coefficients obtained from structural equation modeling by decomposition of latent variables into basic modules to obtain the overall value of Halgrims Cathedral  $y = (8.116, 7.209, 7.093, 8.814, 7.814)$ , the overall value  $y = 7.809$  was further calculated.

### 6.3 Kmeans Cluster Analysis

Cluster analysis is an unsupervised learning method for dividing the samples in a dataset into groups or clusters such that the samples within each cluster are as similar as possible and the samples between different clusters are as different as possible. In this paper, Kmeans clustering algorithm is used to cluster analyze the buildings and classify them into two categories which are of conservation significance and those which are not.

In this section, 40 buildings (20 with conservation significance and 20 without) were selected, and the overall value scores of each building were derived as a cluster analysis dataset by combining them through the methodology proposed above, and the overall value scores extracted from the dataset were used as features. According to the problem claimed to be solved in this paper, it is desired to categorize the buildings into two classes which are of conservation significance and those which are not, hence  $K=2$ .

Cluster labels to which each building belongs are obtained after completing the model training. 0 or 1 represents buildings that are not preserved and buildings that are preserved, respectively. The model we obtained is then applied to help the leaders of the deciding community to identify the buildings in the community that should be preserved and protected because of their culture, history, economy or culture.



**Figure 19.** Kmeans Result

## 7 Application of Models: St. Louis Cathedral

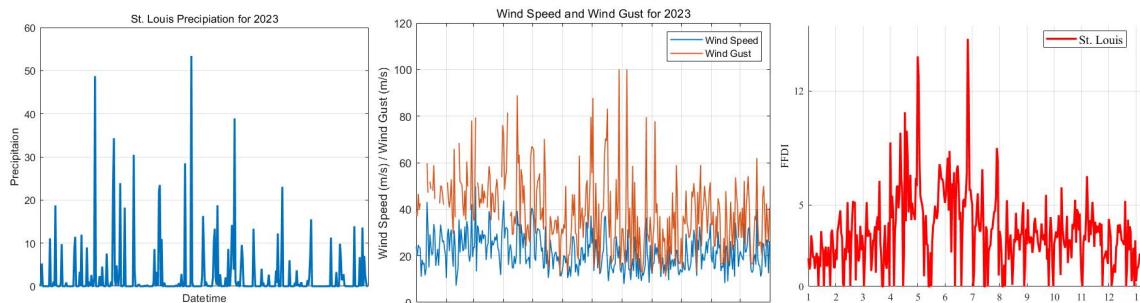
This paper selects the historic landmark of **St. Louis** Cathedral, located in St. Louis, Missouri, USA, and applies the insurance and preservation model proposed above to assess the value of this landmark.

We selected meteorological data for the year 2023 for the City of St. Louis and applied **Models I (Table 14)** and **II (Figure 16)** to analyze the area. The results (Table 14) indicate that the City of St. Louis has a relatively high risk of weather extremes, and that this risk is primarily in the areas of hurricanes and flooding, while the risk of being affected by fire extremes is relatively low.

	Excess Rainfall	High Winds	Wildfires	$(P, C)_{best}$	L(Average)
St. Louis	11	32	4	(663.21, -246,749,200.40)	3,173,550,981.48
C_cut	21.47	58.77	12	(1411, 0)	1,308,966.80

Table 14. Counts of extreme weather events in two regions

Combined with Table 14 and Figure 21, the relative vulnerability of St. Louis to hurricanes, when compared to the average, requires protection of wind-prone measures within the Cathedral. At the same time, according to the analysis of the data derived from (9), conducting insurance business locally carries a high level of risk (negative profit expectations with much higher than average exposure values). This suggests that if the cathedral is not subjected to measures of relocation, but chooses to remain in the area, it needs to be consciously protected by reinforcement against extreme weather conditions. From an insurer's perspective, guaranteeing St. Louis Cathedral carries a high level of risk. However, **from the point of view of the administrators of the St. Louis Cathedral, the need to insure the building is extremely high.**



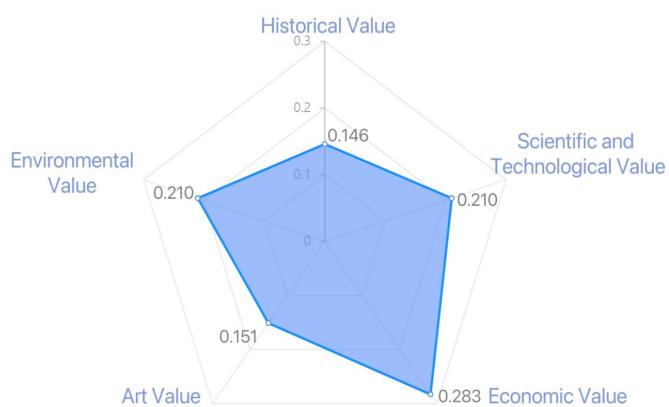
**Figure 20-22.** Precipitation(20), wind speed(21), and fire projections(22) in 2023[5]

The assessment of St. Louis Cathedral was made by five simulation experts, and the assessment scores are shown in Table 7. Based on their scores and the three methods of determining the weights of the assessment indexes, we can calculate the overall value of the building to be 7.781, and conclude that the building has a preservation value after validation by Kmeans clustering.

LLM	Historical Value	Scientific and Technological Value	Economic Value	Art Value	Environmental Value
bard-feb-2024	8	7	9	9	8
gpt-4-1106-preview	9	6	7	8	7
gpt-3.5-turbo-0125	9	7	6	10	8
gemini-pro-dev-api	9	8	7	9	8
mistral-medium	8	6	7	9	8

**Table14.** Evaluation scores (0-10) of Halgrims Cathedral by 5 simulation experts

The weighting of the building's sub-values is shown in the figure, from which it can be seen that the economic value accounts for the highest proportion, the historical value and the scientific and technological value also account for a relatively high proportion, and the artistic value and the environmental value are also of corresponding importance. Therefore, community leaders can take appropriate measures to protect the building and give full play to its value.



**Figure 23.** The Weighting of the Building's Sub-values

# Dear Mayor Jones,

We are writing to address a matter of great importance regarding one of cherished historic landmark—St. Louis Cathedral. In light of the recent advancements in insurance and preservation modeling, we have had the opportunity to conduct a comprehensive assessment of St. Louis Cathedral.

Based on the results of analyzing the insurance model, we created a protection schedule for your city's St. Louis Cathedral based on the month, giving protection measures for different scenarios of extreme weather conditions that may occur, as well as estimated costs.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Extreme Weather Conditions	Rainstorm				✓	✓	✓					
Protective Measure	Gale	✓	✓	✓	✓		✓	✓	✓			
	Conflagration		✓	✓	✓	✓	✓	✓		✓		
	Rainstorm	Regular inspection of church roofs and drainage systems; Enhanced waterproofing of church facades.										
Estimated Cost	Gale	Regularly inspect and maintain the church's exterior structures and buildings; Regular the church's building frame and support structures.										
	Conflagration	Conflagration Installation of fire alarm systems and automatic fire extinguishing equipment; Regular fire safety inspections and drills.										
	Rainstorm	Between \$9,375 and \$15,625.										
Estimated Cost	Gale	Range from tens to hundreds of thousands of dollars.										
	Conflagration	Range from a few thousand dollars to tens of thousands of dollars.										

In our model for evaluation of buildings, we find that the St. Louis Cathedral holds significant economic, historical, cultural, and environmental value, making it imperative to leverage its potential for sustainable development and preservation. Maximizing its economic value involves capitalizing on its allure as a tourist attraction through enhanced publicity via websites, social media platforms, and tourist brochures. Additionally, educational initiatives such as lectures on its historical background and architectural significance serve to deepen public understanding and appreciation, fostering a culture of respect and preservation. Moreover, active participation in environmental protection initiatives ensures the Cathedral's sustainable development, minimizing its ecological footprint and safeguarding the surrounding natural landscape.

We welcome the opportunity to discuss these proposals in further detail and collaborate on charting a path forward for the preservation and protection of St. Louis Cathedral. Your leadership and support in this endeavor are paramount to the success of our collective efforts.

Warm regards,

A Team of Undergraduates Passionated about Mathematical Modeling

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## Report on Use of AI

The simulation expert scoring system used in Model III of this paper uses a large language model to score 40 buildings using a total of five large language models, one of which will be used as a sample in this report.

### 1. *Google Bard (Feb 2, 2024 version)*

Query1: You are a very authoritative expert in the field of architecture, and now you want to score a certain building, scoring a total of five aspects: historical value, scientific value, economic value, artistic value and environmental value, each index scoring 0-10 points, of which the historical indicators in this study is mainly based on the age of the building to assess and analyze the characteristics of the building; the scientific value of the indicators of scientific value is based on the building to reflect its own era of the Scientific value indicators are based on the scientific and technological level of the building in its own era and its reference value to scientific and technological research; economic value indicators are based on the direct and indirect income of the building through the income method; and artistic value indicators are based on the socio-political and economic background of the building, the artistic style of the era, the level of craftsmanship and technology, the uniqueness of the aesthetic point of view, and the contribution to the art and culture of past generations. The environmental value score is based on the building's character as part of the ecological environment, including its impact on the ecological environment and its function for human enjoyment and pleasure, as well as its contribution to the local tourism economy. You are asked to score the Hallgrimms Cathedral in Iceland.

Output format: "X points for historical value, X points for scientific value, X points for economic value, X points for artistic value, X points for environmental value, and the reason for the score:" (where X is the score you gave based on the description of the building and the scoring criteria for each indicator)

Output: ## Hargrimes Cathedral Rating.

\*\*Historical value: 8 points\*\*

Built between 1945 and 1986, Hallgrimms Cathedral is a landmark in Reykjavik, the capital of Iceland. Its design is inspired by Iceland's unique natural landscape, such as basalt stone columns and glaciers, and has a distinctive period character. Named after the famous Icelandic poet Hallgrímur Petersson, the church is of great historical commemorative significance.

\*\*Scientific value: 7 points\*\*

Hallgrimms Cathedral utilized the more advanced technologies of the time in its architectural design and construction techniques, such as reinforced concrete structures and prefabricated panel technology. At 73 meters high, the church is the tallest building in Iceland, and its unique structural design allows it to withstand the strong Icelandic winds.

\*\*Economic value: 9 points\*\*

Hallgrimms Cathedral is one of the most popular tourist attractions in Iceland, attracting hundreds of thousands of visitors each year. The church's admission revenue and the development of the neighboring tourism industry bring significant benefits to the local

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economy.

**\*\*Artistic value: 9 points\*\***

Hallgrímms Cathedral is a masterpiece of modern Icelandic architecture, with its unique architectural style and exquisite interior decoration of high artistic value. The organ inside the church is one of the largest in Europe and a world famous concert venue.

**\*\*Environmental value: 8 points\*\***

Located in the center of Reykjavík, Hargrims Cathedral is an important landscape node in the city. The church's towering towers mark the city's skyline and add a unique charm to the city. The green environment around the church also provides a place for citizens to relax and unwind.

## 2. *OpenAI ChatGPT (Nov 5, 2023 version, ChatGPT-4)*

Query1: Same as the first one.

Output: Historical value: 8 points. The church is relatively new, but has become an important symbol of the Icelandic nation and reflects the architectural styles and social developments of the mid-20th century with its unique design and building techniques. Although it does not have a long history, it occupies a prominent place in modern Icelandic history.

Scientific value: 7 points. Hargrims Cathedral utilizes modern building techniques and materials, and its structure and design demonstrate the scientific and technological level of the time. Its tall tower and spire structure, in particular, is a showcase for engineering and architecture, and while it may not contain cutting-edge technology, it still reflects a certain level of skill.

Economic Value: 6 points. The church itself may have limited direct economic gain as a place of worship, but as a prominent tourist attraction, its indirect economic contribution to the local tourism industry is significant, attracting a large number of tourists and increasing associated tourism revenue.

Artistic value: 9 points. Inspired by the natural landscape of Iceland, such as glaciers and basalt stone columns, the design of Hallgrímms Cathedral is unique in its shape and form and has become an important landmark in Reykjavík. Its artistic value lies in the originality of its design and its expression of Icelandic culture.

Environmental value: 8 points. The church's design harmonizes with its surroundings and forms an important part of Reykjavík's cityscape. It not only provides an ornamental feature, but also becomes an important part of the community and has a positive effect on enhancing the urban environment and promoting the local tourism economy.

## 3. *OpenAI ChatGPT (Oct 23, 2023 version, ChatGPT-3.5)*

Query1:Same as the first one.

Output:In response to the Halgrímms Cathedral building located in the capital of Iceland, I will rate it according to the rating scale provided:

Historical value: 8 points. Halgrímms Cathedral was built in the middle of the 20th century and has a deep historical background, representing the architectural style and technical level of the time, and is of great significance to Icelandic history and culture.

Scientific value: 6 points. Although Hallgrímms Cathedral is not primarily characterized

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by its scientific function, the architectural techniques and structural design involved in its construction reflect the scientific level of the time and are of some reference value to building engineering.

Economic value: 7 points. As one of the landmarks of the Icelandic capital, Hallgrimms Cathedral attracts a large number of tourists every year, contributing positively to the local tourism economy and bringing some indirect benefits to the neighboring businesses.

Artistic value: 9 points. Hallgrimms Cathedral is known for its unique architectural style and artistic design, reflecting Icelandic cultural and aesthetic values, as well as being one of the best examples of local art and craftsmanship.

Environmental value: 7 points. As a landmark of Iceland's capital, Hallgrimms Cathedral not only adds a beautiful scenery to the city, but also has certain ecological and environmental functions, as well as being one of the major attractions for tourists.

#### 4. *Google Gemini Pro (Feb 5, 2024 version)*

Query: Same as the first one.

Output: Historic Hallgrimes Cathedral building scores are listed below:

##### Scoring Criteria

0 - 5 points: very poor

6 - 7 points: poor

8 - 9 points: good

10 score: very good

##### Halgrims Cathedral Building Score

9 Score: Built between 1945 and 1986, the Hallgrimms Cathedral building is the largest church in Iceland and one of Reykjavík's landmarks. Named after the Icelandic poet Halgrimm Petursson, the church was inspired by Iceland's volcanoes and glaciers. The interior of the church is adorned with murals and sculptures created by Icelandic artists and is one of Iceland's important works of art.

8 points: The Hallgrimms Cathedral building is one of Iceland's important scientific research sites. The church houses a science gallery with exhibits about Iceland's geology, climate, flora and fauna. In addition, the church regularly hosts scientific lectures and seminars, making it one of Iceland's important places for scientific exchange.

9 points: Hallgrimms Cathedral building is one of the important tourist attractions in Iceland. The church receives more than one million visitors from all over the world every year. The income from the church is partly used to finance the development of tourism in Iceland, in addition to the daily maintenance and operation of the church.

10 points: The Hallgrimms Cathedral building is one of Iceland's important works of art. The design and decoration of the church fully reflects Iceland's national character and artistic style. The frescoes and sculptures inside the church are from famous Icelandic artists and have high artistic value.

9 points: Hallgrimms Cathedral building is one of the important ecological landscapes in Iceland. The beautiful surroundings of the church are a favorite place for Icelandic people to walk and rest. The church also regularly hosts cultural performances such as concerts and theater performances, making it one of Iceland's important public spaces.

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5. *Google Gemini Pro (Feb 5, 2024 version)*

Query: Same as the first one.

Output: Historical value 8 points, scientific value 7 points, economic value 8 points, artistic value 9 points, environmental value 8 points, reasons for scoring:

Historical Value: Hallgríms Cathedral is one of the oldest churches in Iceland, built in 1787, and has significant historical value. Although its historical age is not too old, as one of the earliest churches in Iceland, it is a landmark for the development of Iceland's religious culture.

Scientific value: Hallgríms Cathedral was built with unique construction techniques, using new building materials and technologies of the time, such as the use of fused lime and firebrick mixtures. In addition, the design of the church is scientifically innovative, for example the large windows are made of special glass, which allows light to pass through the glass into the interior of the church and creates a unique effect of light and shadow.

Economic value: Hallgríms Cathedral is an important tourist attraction in the capital city of Iceland, attracting a large number of tourists every year and making an important contribution to the local tourism economy. In addition, the church is an important center of cultural and religious activities in Iceland, providing an important cultural and social space for the local community.

Artistic value: The architecture of Hallgríms Cathedral is unique and expresses the artistic style and craftsmanship of the time. The large glass windows of the church are beautifully painted, showing the artistic Family style and religious beliefs of the time. In addition, the church has great acoustics and is an excellent venue for local concerts and weddings, with a unique artistic value.

Environmental value: Hallgríms Cathedral is located in the heart of Iceland's capital city, in a privileged natural environment, surrounded by green meadows and flowers for comfort and relaxation. In addition, the cathedral is an important historical and cultural landmark in the area and has significant environmental value.