Fire Alarm System Optimization in the United States

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1 Introduction

False fire alarms are a persistent issue in the United States, with an estimated 60-90% of alarms being false. These events place a significant burden on emergency services, costing the public sector over $1.8 billion annually. This paper introduces a classification-based system to address false alarms and enhance efficiency by integrating machine learning models and automated notification mechanisms.

2 Mathematical Formulation of the Problem

2.1 False Alarm Rate

The false alarm rate F is defined as the proportion of alarms that are classified as false:

$$F = \frac{\text{Number of False Alarms}}{\text{Total Number of Alarms}}$$

Given that $F \in [0.6, 0.9]$, the system aims to reduce F to a target range $F_{\text{target}} \in [0.3, 0.4]$.

2.2 Cost of False Alarms

The total cost C_{false} of false alarms can be expressed as:

$$C_{\text{false}} = N_{\text{false}} \cdot C_{\text{response}}$$

where:

- N_{false} is the number of false alarms.
- C_{response} is the average cost of responding to a single false alarm.

2.3 Savings from the System

If the system reduces false alarms by a fraction r, the total cost savings S are given by:

$$S = r \cdot C_{\text{false}}$$

Substituting C_{false}, we get:

$$S = r \cdot N_{\text{false}} \cdot C_{\text{response}}$$

Assuming $N_{\text{false}} = 1,000,000$ and $C_{\text{response}} = 1,800$, the savings at $r = 0.5$ (50% efficacy) are:

$$S = 0.5 \cdot 1,000,000 \cdot 1,800 = 900,000,000 \,\text{USD annually.}$$

3 Classification Model

The system uses a Random Forest Classifier, denoted as $f(\mathbf{x}; \theta)$, where $\mathbf{x}$ is the feature vector, and θ represents the model parameters. The output of the model is:

$$y = f(\mathbf{x}; \theta) \in \{0, 1\}$$

where:

- $y = 0$: Real Alarm.
- $y = 1$: False Alarm.

The feature vector $\mathbf{x}$ includes:

$$\mathbf{x} = [x_1, x_2, \ldots, x_n]$$

where:

$$\begin{aligned}
&x_1 : \text{Building Type (Residential, Commercial, Industrial)} \\
&x_2 : \text{Historical False Alarms (Numerical)} \\
&x_3 : \text{Occupancy (Numerical)} \\
&x_4 : \text{Fire Resistance (Continuous Scale)} \\
&x_5 : \text{Sprinkler Presence (Binary)} \\
&x_6 : \text{Alarm Source (Categorical)}
\end{aligned}$$

The model is trained to minimize a classification loss function L, typically cross-entropy:

$$L(\theta) = -\frac{1}{m} \sum_{i=1}^{m} \left[y_i \log(f(\mathbf{x}_i; \theta)) + (1 - y_i) \log(1 - f(\mathbf{x}_i; \theta)) \right]$$

4 Fire Alarm Event Workflow

4.1 Event Classification

When a fire alarm is triggered, the workflow can be expressed as:

$$P(y = 1|\mathbf{x}) = f(\mathbf{x}; \theta)$$

where $P(y = 1|\mathbf{x})$ represents the probability that the alarm is false.

If $P(y = 1|\mathbf{x}) > 0.5$, the system predicts a false alarm and initiates a 1-minute grace period.

4.2 Notification and Grace Period

During the grace period, alerts are sent to the residents. Let T represent the total number of residents notified, and R the number of residents responding:

$$R = \sum_{i=1}^{T} r_i$$

where $r_i \in \{0, 1\}$ indicates whether the i-th resident responded.

If $R > 0$ and a false alarm is confirmed, emergency dispatch is canceled. Otherwise, emergency services are dispatched.

4.3 Preventing Emergency Dispatch

The decision to dispatch or cancel is given by:

$$D = \begin{cases} \text{Cancel}, & \text{if } R > 0 \text{ and confirmation is false} \\ \text{Dispatch}, & \text{otherwise.} \end{cases}$$

5 Proposed Cost Savings

Given $C_{\text{false}} = 1.8\,\text{billion USD}$ annually, and assuming a reduction rate $r = 0.5$, the savings S are:

$$S = 0.5 \cdot 1.8\,\text{billion USD} = 0.9\,\text{billion USD annually.}$$

Further, if the reduction rate improves to $r = 0.6$, the savings increase to:

$$S = 0.6 \cdot 1.8\,\text{billion USD} = 1.08\,\text{billion USD annually.}$$

6 Conclusion

The integration of machine learning and automated notifications provides a robust system for addressing false fire alarms. By reducing the false alarm rate and improving resource allocation, this system offers significant cost savings, enhanced safety, and greater public trust.