

HYBRID MODELING METHODOLOGY FOR PREDICTING RISKS IN EMERGENCY MANAGEMENT

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In the contemporary era, global climate change and rapid urbanization have complicated the dynamics of emergency situations. Reports from the UNDRR and IPCC indicate a rise in hydrometeorological events and large-scale fires. Traditional research utilizes deterministic methods based on physical laws (Drysdale, 2011) or stochastic methods based on historical data. However, deterministic models often treat variable parameters (wind, humidity) as constants, failing to reflect real-world randomness. Conversely, statistical methods struggle to predict unique events. This necessitates the development of hybrid models that integrate physical laws with probabilistic calculations for real-time risk assessment.

The proposed methodology integrates the deterministic heat conduction equation with stochastic modeling of environmental uncertainties. *Deterministic Component:* The fundamental process of heat transfer in a combustible object is described by the parabolic partial differential equation:

$$\rho C_o \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T(x,t)}{\partial x} \right) + Q_{general} \quad (1)$$

The boundary condition at the external surface ($x=0$) accounts for radiative q_{rad}'' and convective q_{conv}'' heat fluxes. Convective heat transfer is defined as $q_{conv}'' = h_c (T_{env} - T_{surf})$, where h_c is the heat transfer coefficient.

Stochastic Component: To model uncertainties, environmental parameters are treated as random variables. Wind speed v is modeled using the Weibull distribution (Carta et al., 2009), while ambient temperature T_{env} follows a Gaussian distribution.

Monte Carlo Simulation: A computational experiment was conducted using Python (NumPy, SciPy). The algorithm involves:

1. Input: Defining material properties, geometric dimensions, and fire scenarios.
2. Sampling: Generating 10,000 random samples for wind speed and temperature based on their respective probability distributions.
3. Iterative Calculation: Solving the heat conduction equation for each iteration using the Finite Difference Method (FDM) to determine the time to failure t_{fail} .
4. Analysis: Constructing the Cumulative Distribution Function (CDF) and analyzing «Tail Risk.»

The experiment simulated a fire incident in an industrial zone. *Static vs. Probabilistic Approach:* Under average deterministic conditions $v_{mean} \approx 7.5$ m/s, T_{mean}

= 30°C, the calculated failure time was 1470 seconds (24.5 minutes). This static value is typically used for evacuation planning. However, the hybrid model revealed that failure time is a stochastic quantity ranging from 15 to 45 minutes.

- Mean time: 25.1 minutes.
- 95% Confidence Interval: 18.5 – 32.3 minutes.
- Tail Risk: In approximately 5% of simulations, the object failed in less than 18 minutes.

The discrepancy between the static prediction (24.5 min) and the worst-case scenario (<18 min) highlights the danger of relying solely on deterministic models. The hybrid model identifies critical risks that traditional methods miss.

Physical Interpretation: A counter-intuitive correlation was observed: higher wind speeds were associated with delayed failure times. Physically, while wind increases flame spread, in this specific tank heating scenario, strong wind enhanced convective cooling (h_c), mitigating the radiative heat load.

The research confirms that hybrid modeling successfully combines the accuracy of physical equations with the comprehensiveness of stochastic methods. While the static model predicts a 24.5-minute safety window, the hybrid model reveals a 5% probability of failure within 18 minutes. Identifying this «Tail Risk» is crucial for saving lives. The methodology offers a more realistic tool for dynamic risk assessment in emergency management.

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