Algorithms for Fire Risk Assessment, Prediction and Management Decision-Making

Tolaniddin Nurmuxamedov[1,3], Oybek Koraboshev[2], Zilola Sultonova [1,3], Javlon Gulyamov [1,3] and Marguba Agzamova [1,3]

[1]Tashkent State Transport University, 100167 Tashkent, Uzbekistan
[2]Tashkent State Agrarian University, 100140 Tashkent, Uzbekistan
[3]University of Diyala, Baghdad Old Road, 32001 Baqubah, Iraq
ntolaniddin@mail.ru , sultonovazr@gmail.com, javlonbek1207@gmail.com, mmarguba77777@gmail.com, koraboshevoybek@gmail.com

Keywords: Machine Learning, Fire Risk, Forecasting, Prediction, Decision Support, Optimization, Emergency Situations.

Abstract: This article is devoted to the development of a set of integrated algorithms that support rapid and well-founded management decision-making in emergency situations, assessing fire risk, predicting its dynamics, and making emergency management decisions. The fire risk assessment module calculates risk indicators using statistical and machine learning methods, while the prediction block is based on physical-empirical fire spread models and time series analysis. The decision support part generates recommendations through multi-criteria optimization. Using real-time scenario simulation, various fire scenarios are compared and the most effective operational measures are selected. The system can be adapted to the conditions of urban infrastructure, industrial facilities, and natural forest fires. The obtained scientific results can be used in emergency services, industrial safety, and "smart city" platforms. The study also explores the possibilities of using artificial intelligence, machine learning, statistical analysis, and expert assessment methods in fire risk monitoring systems. The implementation of algorithms in practice creates the opportunity to increase the effectiveness of fire prevention, reduce the impact of the human factor, and organize rapid action in emergency situations. This work is aimed at scientific research in the field of fire safety management, the development of information systems, and improving decision-making mechanisms based on risk analysis.

1 INTRODUCTION

Currently, the issue of fire safety is relevant for industrial enterprises, production facilities, residential buildings, and natural areas. The material damage, environmental damage, and risks to human life caused by fires require effective management decisions in this area. Therefore, rapid assessment of fire risk, its prediction, and timely elimination are important factors in preventing emergency situations. Traditional approaches are often limited by delays in response or uncertain decisions. Modern technologies, including artificial intelligence, data analytics, IoT devices, and optimized algorithms, are increasingly enabling fire risk assessment and management decision support. These approaches help predict the likelihood of fire spread, optimize the necessary resources, and develop an evacuation plan to ensure human safety.

This article discusses the development, testing, and evaluation of algorithms for rapid fire risk detection, prediction, and management decision support. These algorithms will be of great importance not only for increasing the efficiency of fire suppression, but also for reducing material and human losses [1], [2].

2 METHODS AND RESULTS

Fire is an uncontrolled, rapidly spreading and seriously damaging combustion process, the origin of which depends on various factors. In order to ensure fire safety and prevent it, it is important to have a deep understanding of the main factors affecting the combustion process. Therefore, the additive method and the Frendsen model are used to ensure fire safety in facilities with high fire risk.

Among the factors that cause a fire, the amount of oxygen, combustible gases, humidity and temperature play a key role. For the combustion process to occur, the air must contain at least 16% oxygen. If the amount of oxygen increases, the combustion process can accelerate and cause the fire to spread rapidly. Therefore, controlling the amount of oxygen in the environment is of great importance when determining fire safety measures.

Methane and other flammable gases have a significant impact on the occurrence and spread of fire. Methane reacts easily with oxygen in the air, forming a high-temperature flame. Methane is highly explosive at certain concentrations, which requires serious safety measures in industrial and domestic gas systems. The effect of moisture on fire is complex, determining the flammability of materials and the rate of fire spread. High humidity levels generally help prevent fires, as combustion is slowed down in a humid environment. However, dry materials can ignite more quickly in low humidity conditions, which increases the risk of forest fires and industrial fires [3]-[5].

Temperature is also an important factor in fire safety, as high temperatures can cause combustible materials to spontaneously ignite. Heat sources, such as electrical equipment or open flames, can cause materials to burn more quickly. Increasing temperatures reduce the amount of moisture in the air, further increasing the likelihood of fire spreading. Thus, factors such as oxygen, methane, moisture, and temperature play a key role in the initiation and spread of fire. In-depth study of these factors and the development of fire safety measures based on them is important for protecting human life and property. Based on the equations presented below, a model for calculating fire risk for a given time period is presented, taking into account the values of the factors at the current time and the constant effects.

Considering the constant sources and absorption of factors such as oxygen, methane, moisture, and temperature, the following was obtained.

Expression of methane:

$$\frac{dX_1}{dt} = E_{X_1}(t) - \kappa X_1. \tag{1}$$

Expression of oxygen:

$$\frac{dX_2}{dt} = S_{X_2}(t) - \theta X_2 + \sigma. \tag{2}$$

Expression of humidity:

$$\frac{dX_3}{dt} = W_{X_3}(t) - \eta \cdot X_3 - \lambda X_4 \cdot X_3. \tag{3}$$

Expression of temperature:

$$\frac{dX_4}{dt} = Q_{X_4}(t) + \alpha X_4 - \delta X_3 - \zeta X_4. \tag{4}$$

A model for fire risk:

$$\frac{dF}{dt} = a_1X_4 + a_2X_2 + a_3X_1 - a_4X_3 - \phi F + R_F(t). \tag{5}$$

For the above functions, the initial values under normal conditions are as follows:

$$X_1(0) = 5\left[\frac{g}{m^3}\right], X_2(0) = 270\left[\frac{g}{m^3}\right], X_3(0) = 400\left[\frac{g}{m^3}\right], X_4(0) = 30[°C], F(0) = 10[\%].$$

The following time-varying functions are given for the free terms expressing the influence of external factors on the process:

$$S_{X_2}(t) = \frac{S_{max}}{1 + e^{-a(t-t_0)}}, \tag{6}$$

here:

- $S_{X_2}(t)$ - a constant source of oxygen,
- S_{max} - the maximum amount of oxygen input,
- a - 0.1, rate of growth,
- t_0 - (10,300), transition stage.

$$E_{X_1}(t) = E_0 te^{-bt}, \tag{7}$$

here:

- $E_{X_1}(t)$ - methane emissions over time,
- E_0 - 5, initial speed,
- b - 0.05, rate of decline.

$$Q_{X_4}(t) = Q_0 e^{-ct} + d, \tag{8}$$

here:

- $Q_{X_4}(t)$ - amount of heat over time,
- Q_0 - 500, initial heat capacity,
- c - 0.02, rate of decline,
- d - 100, residual stable quantity.

$$R_F(t) = r_0 / \left(14 - \frac{t}{86400}\right), t \neq 1209600,$$

here:

- r_0 - initial exposure level.

The physic-chemical nature and units of measurement of the terms in equations (1) - (5) above are presented in Table 1 below [6]-[9].

Below is a formula-based algorithm for numerically solving model equations based on Euler's method.

Solving using Euler's method:

$$X_1(t + \Delta t) = X_1(t) + \Delta t \cdot (E_{X_1}(t) - \kappa X_1)$$

$$X_2(t + \Delta t) = X_2(t) + \Delta t \cdot (S_{X_2}(t) - \theta X_2 + \sigma)$$

Table 1: Physic-chemical nature of terms and units of measurement.

Terms	Unit of measurement	Physic-chemical explanation
$\frac{dX_2}{dt}$	g/(m³·s)	The rate of change in oxygen concentration over time (increase or decrease in oxygen).
$-\theta X_2$	g/(m³)	Natural decrease in oxygen (due to diffusion or other processes).
σ	g/(m³)	A constant supply of oxygen from an external source (e.g., airflow).
$S_{X_2}(t)$	g/(m³·s)	Time-dependent oxygen supply from an external source (e.g., through trees).
$\frac{dX_1}{dt}$	g/(m³·s)	The rate of change in methane concentration over time (increase or decrease in methane).
$-\kappa X_1$	g/(m³·s)	Natural decline of methane (due to diffusion or decomposition).
$E_{X_1}(t)$	g/(m³·s)	Methane emissions from an external source (e.g., gas leak) that are time-dependent.
$\frac{dX_3}{dt}$	kg/(m³·s)	The rate of change in moisture concentration over time (increase or decrease in humidity).
$-\eta X_3$	kg/(m³·s)	Natural decrease in humidity (due to evaporation).
$-\lambda T X_3$	kg/(m³·s)	Evaporation of moisture is dependent on temperature (higher temperatures lose moisture faster).
$W_{X_3}(t)$	kg/(m³·s)	Time-dependent moisture supply from an external source (e.g. rain or water spray).
$\frac{dX_4}{dt}$	°C/s	The rate of change of temperature over time (temperature increase or decrease).
αX_4	°C/s	Spontaneous increase or decrease in temperature (natural thermal variation).
$-\delta X_3$	°C/s	Humidity reduces temperature (cooling effect, through evaporation).
$-\zeta X_4$	°C/s	Temperature decrease due to heat dissipation (convection or radiation).
$Q_{X_4}(t)$	°C/s	Time-dependent heat supply from an external source (e.g., sunlight).
$\frac{dF}{dt}$	1/s	The rate of change of the fire risk index over time (increasing or decreasing risk).
$a_1 X_4$	1/s	The effect of temperature on fire risk (higher temperatures increase the risk).
$a_2 X_2$	1/s	The effect of oxygen on fire risk (oxygen increases the risk of combustion).
$a_3 X_1$	1/s	The effect of methane on fire risk (methane increases the risk as a flammable gas).
$-a_4 X_3$	1/s	Negative effect of humidity on fire risk (humidity reduces risk).
$-\phi F$	1/s	Natural reduction in fire risk (e.g. due to risk-reducing factors).
$R_F(t)$	1/s	Increased fire risk due to time-dependent external factors (e.g. human activity or dry weather).

$$X_3(t+\Delta t) = X_3(t) + \Delta t \cdot (W_{X_3}(t) - \eta \cdot X_3 - \lambda X_4 \cdot X_3)$$

$$X_4(t+\Delta t) = X_4(t) + \Delta t \cdot (Q_{X_4}(t) + \alpha X_4 - \delta X_3 - \zeta X_4)$$

$$F(t+\Delta t) = F(t) + \Delta t \cdot (a_1 X_4(t) + a_2 X_2(t) + a_3 X_1(t) - a_4 X_3(t) - \phi F(t) + R_F(t))$$

Algorithm:

1) Step 1. $t = 0$, Δt, t_{max} is determined.
2) Step 2. $X_1(0)$, $X_2(0)$, $X_3(0)$, $X_4(0)$, $F(0)$ are entered.
3) Step 3. θ, σ, κ, η, λ, α, δ, ζ, a_1, a_2, a_3, a_4, ϕ are entered.
4) Step 4. $E_{X_1}(t)$, $S_{X_2}(t)$, $W_{X_3}(t)$, $Q_{X_4}(t)$, $R_F(t)$ are defined.
5) Step 5. Until $t < t_{max}$:

$$X_1(t+\Delta t) = X_1(t) + \Delta t \cdot (E_{X_1}(t) - \kappa X_1)$$

$$X_2(t+\Delta t) = X_2(t) + \Delta t \cdot (S_{X_2}(t) - \theta X_2 + \sigma)$$

$$X_3(t+\Delta t) = X_3(t) + \Delta t \cdot (W_{X_3}(t) - \eta \cdot X_3 - \lambda X_4 \cdot X_3)$$

$$X_4(t+\Delta t) = X_4(t) + \Delta t \cdot (Q_{X_4}(t) + \alpha X_4 - \delta X_3 - \zeta X_4)$$

$$F(t+\Delta t) = F(t) + \Delta t \cdot (a_1 X_4(t) + a_2 X_2(t) + a_3 X_1(t) - a_4 X_3(t) - \phi F(t) + R_F(t))$$

$$t = t + \Delta t$$

6) Step 6. The minimum and maximum values of the functions $X_1(t)$, $X_2(t)$, $X_3(t)$, $X_4(t)$, $F(t)$ are checked. $X_{1\_min} < X_1(t) < X_1\_max$, $X_{2\_min} < X_2(t) < X_{2\_max}$, $X_{3_{min}} < X_3(t) < X_{3_{max}}$, $X_{4_{min}} < X_4(t) < X_{4_{max}}$, $F_{min} < F(t) < F_{max}$. If the results are satisfactory, the values of the functions $X_1(t)$, $X_2(t)$, $X_3(t)$, $X_4(t)$, $F(t)$ are kept and the calculation is

forwarded to the next step, i.e. step 5. Otherwise, the calculation is stopped and the calculation is restarted by checking the incoming values and time step values. Only when the F(t) value is above the criterion is the calculation terminated and the results are saved.

7) Step 7. If the condition $t < t_{max}$ is not met, that is, if the condition t = t_calculation is met, the calculation is stopped and the values of the function F are analyzed. The calculation time is completed [10]-[13].

The results of the study show that the use of mathematical models and intelligent algorithms in assessing and predicting fire risk significantly increases the effectiveness of fire safety. Through a systematic analysis of fire risk factors, the individual risk level for each facility is determined and the probability of a fire is more accurately predicted.

A comparative analysis of the prediction results achieved using the proposed algorithm with the machine learning algorithms Random Forest, SVM, and kNN is presented in Table 2.

The results of the conducted research confirmed the effectiveness of algorithmic approaches in the field of fire risk assessment and management. Based on data analysis and modeling, a multi-stage system for determining fire risk was developed, which took into account the interaction of risk factors and indicators such as the state of technical infrastructure and the human factor. The analysis results showed that traditional assessment methods have a high subjective factor, which negatively affects the stability of the results, the proposed algorithmic approach eliminates this drawback and allows for automated decision-making, the use of machine learning and statistical regression methods in predictive models increases the accuracy of fire risk forecasts by 15 - 20%, the time for rapid detection and warning of fire risks using real-time monitoring systems was reduced by 1.5 - 2 times, and the accuracy of the proposed predictive model showed the best result of 94.49%.

Figure 1 below shows a graph of a fire risk prediction model based on 4 input parameters.

Table 2: Comparative analysis of random forest, svm, knn and proposed algorithms.

№	Algorithm	Parameters	Accuracy of training	Control accuracy	Error values of the training sample	Error values of the control sample
1	The proposed algorithm	Input parameters: improved Kalman filter, Prediction model	94.49%	93.01%	0.057	0.076
2	SVM	Kernel: Linear. C: 1.0	85.46%	84.41%	0.145	0.156
3	SVM	Kernel: RBF. C: 1.0. Gamma: 0.1	87.34%	86.03%	0.127	0.139
4	SVM	Kernel: Polynomial. Degree: 3	88.06%	87.79%	0.119	0.122
5	SVM	Kernel: RBF. C: 0.5. Gamma: 0.2	84.83%	83.44%	0.152	0.166
6	Random Forest	Trees: 10. Depth: None	84.28%	83.33%	0.158	0.167
7	Random Forest	Trees: 20. Depth: 10	87.62%	86.28%	0.124	0.138
8	kNN	Nearest neighbors: 3. Distance: Euclid	82.07%	81.90%	0.179	0.181
9	kNN	Nearest neighbors: 5. Distance: Manhattan	83.71%	82.45%	0.162	0.175
10	kNN	Nearest Neighbors: 7. Distance: Euclid	86.54%	85.96%	0.132	0.14
11	MLP	Hidden layers: (64. 32). Activation function: ReLU. Optimizer: Adam	92.29%	90.69%	0.074	0.094

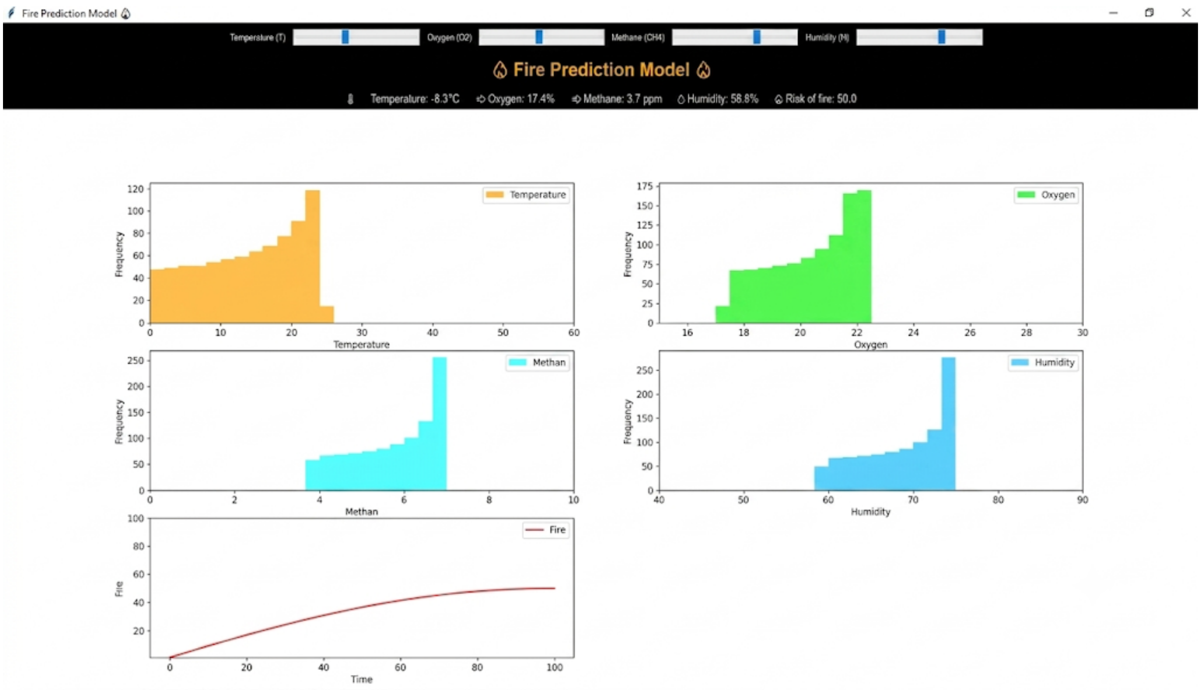

Figure 1: A graph of the fire risk prediction model.

3 CONCLUSIONS

The development of algorithms for fire risk assessment, prediction and management decision-making is an important component of modern security systems. The research results show that algorithms that allow for the correct identification of fire risk factors and their real-time prediction play a crucial role in preventing fires and reducing their consequences. The proposed approaches, based on artificial intelligence, data analysis, simulation and optimization technologies, allow building a model of the fire spread process, predicting the level of risk and making effective management decisions quickly. This ensures high efficiency in rational resource allocation, optimizing the evacuation plan and determining the fire extinguishing strategy.

In general, the introduction of fire risk assessment and prediction algorithms is an important step towards the digitalization of security systems and improving the quality of management in emergency situations. In the future, more efficient systems can be developed by integrating these algorithms with IoT devices, artificial intelligence platforms and big data analysis.

REFERENCES

[1] O. Z. Koraboshev, "Ensuring fire safety using neural networks and genetic algorithms," in Proceedings of the Scientific Conference "Science and Technology in the Fergana Valley", Namangan, Uzbekistan, May 11-12, 2023, pp. 335-338.

[2] D. I. Pavlov, "General principles and approaches to the selection and use of smoke fire detectors for protection facilities," Supervisory Activity and Forensic Examination in the Security System, no. 2, pp. 30-42, 2020.

[3] B. A. Mavlyankariev and B. B. Khatamov, "Method for modeling factors determining the characteristic of multifunctional special equipment in ensuring the required level of fire safety of a complex object," International Journal of Advanced Research in Science, Engineering and Technology, vol. 6, no. 9, pp. 10799-10804, 2019.

[4] A. Sh. Arifzhanov, D. K. Mukhamedieva, and U. U. Khasanov, "Modeling processes of optimizing the structure of forces and means at a fire using parallel computing," High-Performance Computing Systems and Technologies, vol. 5, no. 2, pp. 35-42, 2021.

[5] U. Khasanov, "Application of fuzzy methods for solving incorrect problems," in Proceedings of the 1st International Scientific and Practical Conference "Science in the Environment of Rapid Changes", Brussels, Belgium, 2022, pp. 274-277.

[6] V. V. Kokorin, V. D. Khalikov, I. Ya. Udilova, and S. A. Shevtsov, "Problems of collecting information on fires and accidents at industrial facilities: Ways of their solution," General Issues of Fire Safety, no. 1, pp. 21-25, 2014.

[7] N. V. Streblyanskaya, "Study of the problem of forecasting emergency situations in emergency warning systems for the population," Bulletin of SKFU, no. 1, pp. 80-84, 2015.

[8] N. M. Zhuravlev, "Support for the decision-making of a fire extinguishing manager based on a system-dynamic model of frontal fire extinguishing," in Proceedings of the IV All-Russian Scientific and Practical Conference "Priority Areas for the Development of Russian Science", St. Petersburg, Russia, 2020, pp. 17-21.

[9] S. V. Gudin, R. Sh. Khabibulin, and D. N. Rubtsov, "Problems of fire risk management on the territory of oil refining facilities using modern software products," Fire and Explosion Safety, vol. 24, no. 12, pp. 40-45, 2015.

[10] A. S. Belyaeva et al., "Development of an Intelligent Fire Safety System for Manufacturing Facilities," Research Journal, no. 4, p. 142, 2024, [Online]. Available: https://doi.org/10.23670/IRJ.2024.142.33.

[11] V. Kodur and M. Z. Naser, "Fire hazard in transportation infrastructure: Review, assessment and mitigation strategies," Frontiers of Structural and Civil Engineering, vol. 15, no. 1, pp. 46-60, 2021.

[12] A. Smirnov, R. Khabibulin, N. Topolski, and D. Tarakanov, "Multi-Agent Analysis Model of Resource Allocation Variants to Ensure Fire Safety," in Proceedings of the 21st International Conference on Enterprise Information Systems, Heraklion, Greece, May 3-5, 2019, pp. 379-386, [Online]. Available: https://doi.org/10.5220/0007716403910398.

[13] N. Denisov, "Mathematical formalization of the general scientific concept of the deterministic process of fire extinguishing by mobile means," Bulletin of the Voronezh Institute of the State Fire Service of the Ministry of Emergency Situations of Russia, no. 4, pp. 9-14, 2017.