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Solving the Problem of Multi-Objective Optimization Based on a Fuzzy Logic Model

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Abstract. In this article, an analytical analysis of solving classification tasks for loosely formalized processes is conducted. Throughout the course of this research, structures were devised for the creation of training datasets. These structures facilitate the management of the intricate task of modeling processes, particularly in scenarios where the available data exhibits a fuzzy or uncertain nature. Researchers demonstrated that the successful solution of this task requires the application of special methods and mathematical tools, including the theory of fuzzy sets. Furthermore, the article presents a developed algorithm for solving multi-criteria optimization tasks of loosely formalized processes based on constructing a fuzzy logical model. This algorithm is successfully applied for optimizing the placement of fire and rescue units at designated positions, which has significant practical importance. Additionally, based on the matrix representation of fuzzy logic, the article improved the algorithm for constructing a Mamdani neuro-fuzzy model. This solution was used for the classification of loosely formed processes and the creation of a software complex, opening new perspectives in the field of fuzzy information processing and solving practical tasks related to such processes.
Keywords. fuzzy set theory, fuzzy logic, linear programming, multi-objective optimization.

INTRODUCTION

In practice, it is often necessary to deal with non-precise models that lack exact specifications and involve complexities beyond simply enumerating precise numbers. The application of optimization theory, which is based on non-precise models, is quite relevant in such cases [1].

The topic of fuzzy optimization is currently the subject of several articles. Studying them reveals several issues based on the theory of fuzzy sets that address the following problems[1]:

1. Vector objective function of linear programming problem $f(x) \to \max$ to check. In [1], the vector criterion is transformed into a scalar form by a linear convolution with fuzzy numbers as coefficients.

2. Search for the exact solution of linear programming problems, in which relevance functions are indicated for the criteria and constraints, which describe the possibility of certain deviations from the exact fulfillment of the inequality in general.

3. Determination of exact solutions of fuzzy linear programming problems in various constraints in the form of fuzzy numbers included in the objective function and constraints.

In [2], it is presented to determine the degree of correspondence to an exact exact problem of linear programming, which can be constructed on a fuzzy linear programming problem by choosing some exact value for each fuzzy number. However, here the problem of constructing an appropriate computational method for fuzzy solving of fuzzy parametric and stochastic programming remains unsolved.

Existing computational algorithms for solving nonlinear programming problems can be divided into the following groups:

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1. Application of linear programming apparatus for nonlinear programming problems by using successive linear approximation procedure [2,3]. Quadratic approximation methods are also used to solve the quadratic programming problem at each step.

2. Decomposition of a constrained nonlinear programming problem into a sequence of equivalent simple problems (for example, unconditional optimization) by including penalty functions into consideration [4].

3. Reduction of unconnectedness of network equations by processing them by separate equations and variables, relaxation by components.

A description of a number of existing methods and computer software packages for solving nonlinear programming problems, their capabilities and their comparative analysis are presented in [5,6].

The primary challenge when addressing nonlinear programming problems, particularly in situations where the provided information is ambiguous, persists as follows:

The key focus lies in the development of computational algorithms and the pursuit of a fuzzy analytical solution.

Application of intermediate and fuzzy arithmetics, which allows to perform operations in the process of solving optimization problems with fields of admissible and inadmissible solutions (with a variable degree of admissibility of solutions).

A special issue in the use of simulation modeling is the issue of building a suitable mathematical model of the object being studied in advance and implementing it on a computer using the exact mathematical laws and numbers, fuzzy sets and fuzzy rules created from the logic-linguistic reasoning of experts. Ill-formed systems cannot provide clear correlations between the parameters of the process being modeled. Because of this, there is a significant lag in simulation modeling of non-deterministic phenomena and processes. Due to this, it is proposed to build such a model using fuzzy set theory and fuzzy logic methods.

The peculiarities of solving problems in real time lead to the equivalence of insufficient computing power to insufficient information about the conditions of the problem.

More complex methods of fuzzy mathematics significantly increase the reliability and efficiency of the operational solutions used due to the possibilities of computer application.

All these methods could be divided into two main groups:

1. Reducing the influence of uncertain data by using simple deterministic algorithms.

2. Switching to special algorithms (stochastic, fuzzy, interval) in cases of uncertain data.

When solving problems with a deterministic set, with the increase in the complexity and size of the model, there are big problems related to the stability of the optimization problems. The optimization process itself involves bringing the system to certain limits. In this case, even insignificant fluctuations of the second-order parameters can lead to the loss of the mode. These constraints cannot simply be extended - the optimization procedure immediately pushes the regime to new limits, and the problem of stagnation remains. Therefore, only expressing a series of constraints as fuzzy allows to obtain a stable solution in the form of relevance functions, showing a reduction in the level of admissibility of this mode in the conditions of data error and production constraints' ambiguity. Putting the problem in a fuzzy form also allows to significantly reduce the possibility of obtaining inappropriate solutions in calculations and optimization. [7-11].

Given a simple function $f : X \to R^1$ to maximize the given fuzzy set of admissible alternatives $\mu : X \to [0,1]$.

Mathematical programming is a fuzzy version of the standard problem. Suppose the following mathematical programming problem is defined:

$$f(x) \to \max ,$$
$$\phi(x) \le 0, \quad x \in X .$$

A fuzzy version of this issue is obtained in cases where the restrictions are "softened", that is, in cases where they are allowed to be violated to one degree or another. Also, instead of maximizing the function $f\left(x\right)$, one can seek to achieve a given value of this function by giving varying degrees of tolerance for the function's values to be different from this value.

The "maximizing" function is fuzzyly expressed, i.e $\mu_{\phi} : X \times R^1 \to [0,1]$ is reflected here X – universal set of alternatives, R^1 -number axis.

In this case $\mu_{\phi}(x_0, r)$ each constant of the function in case $\mu_{\phi}(x_0, r)$ x_0 fuzzy expression of the evaluation of the result of choosing an alternative (x_0 (fuzzy evaluation of the alternative) or consists of the fuzzy known response of the control system to the control. A vague set of acceptable alternatives is also given $\mu_c : X \times R^1 \to [0,1]$.

Simple maximizing function $f : X \to R^1$ and $\phi_i(x) \le b_i$, $i = 1,...,m$ given a system of constraints of the form, in which $\phi_i(x)$ parameters in function expressions are given as fuzzy sets.

Fire safety can be seen as a poorly formed process. Analyzing the nature of uncertainties appearing in these processes allows us to conclude that they can be transferred within the framework of the fuzzy-intermediate approach of appropriate mathematical formalization.

METHODS

The purpose of the research is to develop fuzzy logical models and algorithms and a software complex of fire safety on the basis of an intellectual approach. The objective of this research is to formulate an algorithm designed to address the challenge of multi-criteria optimization within loosely structured processes, utilizing the framework of a fuzzy logical model. In this case, the mathematical model of calculating the reasonable number of operative fire-rescue units, fire extinguishing means and assigning them to extinguishing places, that is, the optimization of the composition of forces and means in the fire, is formalized in the form of interacting objects.

The research has successfully yielded an algorithm for tackling the multi-criteria optimization challenge within loosely structured processes. This algorithm is rooted in the construction of a fuzzy logical model, as outlined in reference [12]. The problem of multi-criteria optimization for the efficient deployment of firefighting units at designated locations is formulated in the following manner, as expressed in equations (1) and (2):

$$\begin{aligned} z_1\left(x_{ij}^*\right) &= \left(\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}^1 x_{ij}\right) \xrightarrow[x_{ij}\in D]{} \max, \\ z_2\left(x_{ij}^*\right) &= \left(\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}^2 x_{ij}\right) \xrightarrow[x_{ij}\in D]{}, \min \\ &\ldots\ldots\ldots\ldots \\ z_s\left(x_{ij}^*\right) &= \left(\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}^s x_{ij}\right) \xrightarrow[x_{ij}\in D]{} \min, \end{aligned} \tag{1}$$

$$\begin{aligned} &\sum_{i=1}^{m} x_{ij} \le Q_{1j}, \\ &\sum_{j=1}^{n} x_{ij} \le Q_{2j}, \\ &x_{ij} \ge 0, \\ &i = \overline{1,m},\ j = \overline{1,n}, \end{aligned} \tag{2}$$

here:

$n-$ the number of objects on fire;

$m-$ number of emergency departments;

$S-$ number of criteria;

x_{ij} $-$ $j-$ resource directed from the emergency department to the i-facility;

Q_{1j} $-$ $j-$ resource requirements of the fire facility;

Q_{2i} $-$ $i-$ resources available in the emergency department (ED).;

c_{ij}^s $-$ $i-$ $s-$cost (time, road, water, etc.) per unit of resources directed from the emergency department to $j-$fire facility.

The theory of fuzzy sets is used in the work as a mathematical apparatus that allows to formalize fuzzy data. S independent parameters $\lambda_1,\ldots,$ λ_S parametric model or S parametric problem with , is written in matrix form as follows:

$$z(x_{ij}^{*}) = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} (\lambda_1 c_{ij}^{1} + \lambda_2 c_{ij}^{2} + ... + \lambda_S c_{ij}^{S}) x_{ij} \right) \xrightarrow[x_{ij} \in D]{} \min,$$

$$\sum_{i=1}^{m} x_{ij} \le Q_{1j},$$

$$\sum_{j=1}^{n} x_{ij} \le Q_{2j},$$

$$x_{ij} \ge 0,$$

$$i = \overline{1,m},\ j = \overline{1,n},$$

here: λ_s - s – parameter of the multicriteria objective function.

This $\Lambda^{\bullet} \in D_A$ are found using the following fuzzy rule inferences:

$\bigcup_{p=1}^{k_i} \left(\bigcap_{i=1}^{s} \lambda_i = \Psi_{i,jp} - \text{with weight} \right) \to z_s(\lambda) = z_s(\lambda *)$. Here $\Psi_{i,jp}$ - jp in the numbered line λ_i a linguistic term that gives the value of a variable;

w_{jp} - rule weight coefficient with sequence number jp;

$z_S(\lambda) = z_S(\lambda^*)$ - fuzzy rule inference.

The problem of multi-criteria optimization of weakly formed processes can be solved based on the construction of Sugeno's fuzzy logic model.

The scientific significance of the research results is based on the improvement of the classification model construction algorithm based on the matrix representation of Sugeno and Mamdani's fuzzy logic model.

The practical significance of the research results is explained by the application of classification models and algorithms of slow-formed processes on the basis of a hybrid intellectual approach to solving the problem of fire prevention and fire detection.

RESULTS

The above multi-criteria optimization model was solved based on the information presented in the table below for the case of $m = 3, n = 4$ and $S = 3$.

Using the information in the table above, the optimization problem is solved using three different objective functions for the optimization model.

Maximization objective function with respect to water volume

$$\begin{aligned} z_1 = {} & 0.6x_{11} + 0.7x_{12} + 0.3x_{13} + 0.8x_{14} + \\ & + 0.5x_{21} + 0.4x_{22} + 0.5x_{23} + 0.3x_{24} + \\ & + 0.4x_{31} + 0.3x_{32} + 0.6x_{33} + 0.7x_{34}. \end{aligned}$$

Minimization objective function with respect to time

$$\begin{aligned} Z_2 = {} & 0.1x_{11} + 0.2x_{12} + 0.3x_{13} + 0.1x_{14} + \\ & + 0.2x_{21} + 0.1x_{22} + 0.3x_{23} + 0.3x_{24} + \\ & + 0.3x_{31} + 0.2x_{32} + 0.3x_{33} + 0.3x_{34}. \end{aligned}$$

Minimization objective function with respect to path

$$\begin{aligned} Z_3 = {} & 0.2x_{11} + 0.1x_{12} + 0.1x_{13} + 0.1x_{14} + \\ & + 0.3x_{21} + 0.1x_{22} + 0.1x_{23} + 0.2x_{24} + \\ & + 0.2x_{31} + 0.2x_{32} + 0.1x_{33} + 0.2x_{34}. \end{aligned}$$

General objective function will be in the form of $Z = -\lambda_1 z_1 + \lambda_2 z_2 + \lambda_3 z_3$

TABLE 1. Objective function coefficients and resources

	Object 1	Object 2	Object 3	Object 4	Aviable resources (Q_{2i})
FVB 1	0.6, 0.1, 0.2	0.7, 0.2, 0.1	0.3, 0.3, 0.1	0.8, 0.1, 0.1	40
FVB 2	0.5, 0.2, 0.3	0.4, 0.1, 0.1	0.5, 0.3, 0.1	0.3, 0.3, 0.2	15
FVB 3	0.4, 0.3, 0.2	0.3, 0.2, 0.2	0.6, 0.3, 0.1	0.7, 0.3, 0.2	30
Required resources (Q_{1j})	20	20	10	35	

When a multicriteria optimization problem is solved considering a single objective function, for a chosen objective function λ_S corresponding parameters of the vector are taken as 1 and others are ignored i.e. taken as 0. λ_S the sum of the values of the parameters of the vector is required to be equal to 1 based on the rule of the weight coefficient. In this case $\lambda_1,\ldots,\lambda_S$ vector value is determined as follows:

$$\lambda_1 = 1, \lambda_2 = 0, \lambda_3 = 0,$$

value of optimization model is equal to $z_2 = 56.5$, for this case values of x_{ij} -are given in TABLE 2.

TABLE 2. Values of x_{ij} for parameters $\lambda_1 = 1, \lambda_2 = 0, \lambda_3 = 0$

	Object 1	Object 2	Object 3	Object 4	Aviable resources (Q_{2i})
FVB 1	5	20	0	15	40
FVB 2	15	0	0	0	15
FVB 3	0	0	10	20	30
Required resources (Q_{1j})	20	20	10	35	

For second objective function z_2 the values of the vector λ_S are defined as follows:

$$\lambda_1 = 0, \lambda_2 = 1, \lambda_3 = 0,$$

value of optimization model is equal to $z_2 = 14.0$, for this case values of x_{ij} are given in TABLE 3.

For third objective function z_3 the values of the vector λ_S are defined as follows:

$$\lambda_1 = 0, \lambda_2 = 0, \lambda_3 = 1,$$

value of optimization model is equal to $z_3 = 10.5$, in this case x_{ij} - the values of are given in TABLE 4.

TABLE 3. Values of x_{ij} for parameters $\lambda_1 = 1, \lambda_2 = 0, \lambda_3 = 0$

	Object 1	Object 2	Object 3	Object 4	Aviable resources (Q_{2i})
FVB 1	5	0	0	35	40
FVB 2	0	15	0	0	15
FVB 3	15	5	10	0	30
Required resources (Q_{1j})	20	20	10	35	

TABLE 4. Values of x_{ij} for parameters $\lambda_1 = 1, \lambda_2 = 0, \lambda_3 = 0$

	Object 1	Object 2	Object 3	Object 4	Aviable resources (Q_{2i})
FVB 1	0	5	0	35	40
FVB 2	0	15	0	0	15
FVB 3	20	0	10	0	30
Required resources (Q_{1j})	20	20	10	35	

For general Z objective function λ_S when the values of the vector are determined accordingly:

$$\lambda_1 = 0.5, \lambda_2 = 0.2, \lambda_3 = 0.3,$$

general objective function has the form $Z = -\lambda_1 z_1 + \lambda_2 z_2 + \lambda_3 z_3$:

$$Z = 0.22x_{11} + 0.28x_{12} + 0.06x_{13} + 0.35x_{14} +$$
$$+ 0.12x_{21} + 0.15x_{22} + 0.16x_{23} + 0.03x_{24} +$$
$$+ 0.08x_{31} + 0.05x_{32} + 0.21x_{33} + 0.23x_{34},$$

value of the optimization model for these coefficients is equal to $Z = 28.0$, the values of x_{ij} for this case are given in TABLE 5.

TABLE 5. Values of x_{ij} for parameters $\lambda_1 = 0.5, \lambda_2 = 0.2, \lambda_3 = 0.3$

	Object 1	Object 2	Object 3	Object 4	Aviable resources (Q_{2i})
FVB 1	5	20	0	15	40
FVB 2	15	0	0	0	15
FVB 3	0	0	10	20	30
Required resources (Q_{1j})	20	20	10	35	

λ_S when other values of the vector are specified:

$$\lambda_1 = 0.8, \lambda_2 = 0.1, \lambda_3 = 0.1,$$

general objetive function has the form $Z = -\lambda_1 z_1 + \lambda_2 z_2 + \lambda_3 z_3$:

$$Z = 0.45x_{11} + 0.53x_{12} + 0.20x_{13} + 0.62x_{14} +$$
$$+ 0.35x_{21} + 0.30x_{22} + 0.36x_{23} + 0.19x_{24} +$$
$$+ 0.27x_{31} + 0.20x_{32} + 0.44x_{33} + 0.51x_{34},$$

value of the optimization model for these coefficients is equal to $Z = 42.0$ for this case x_{ij} - for this case are given in TABLE 6.

TABLE 6. Values of x_{ij} for parameters $\lambda_1 = 0.8, \lambda_2 = 0.1, \lambda_3 = 0.1$

	Object 1	Object 2	Object 3	Object 4	Aviable resources (Q_{2i})
FVB 1	5	20	0	15	40
FVB 2	15	0	0	0	15
FVB 3	0	0	10	20	30
Required resources (Q_{1j})	20	20	10	35	

This sequence is continued, λ_S the values of the objective function for the remaining parameters of the vector are found and the training sample presented in Table 7 for the fuzzy logic model is generated as follows.

TABLE 7. Fuzzy knowledge base of multicriteria optimization problem

λ_1	λ_2	λ_3	Z
1.00	0.00	0.00	56.50
0.00	1.00	0.00	14.00
0.00	0.00	1.00	10.50
0.50	0.20	0.30	28.00
0.80	0.10	0.10	42.00
0.34	0.01	0.65	10.53
0.64	0.02	0.34	31.04
0.85	0.07	0.08	45.65
...	...	...	...

In the case of multi-criteria optimization, it is difficult to evaluate the optimal solution of the problem according to the set of criteria. As the most common methods in this regard, we can take the additive check and the methods evaluated by the decision maker (VAT) [5].

This $\Lambda^{\bullet} \in D_A$ are found using the following fuzzy rule inferences:

$\bigcup_{p=1}^{k_i}\left(\bigcap_{i=1}^{S}\lambda_i = \Psi_{i,jp} - \text{with weight}\right) \to z_s(\lambda) = z_s(\lambda *)$. In this case $\Psi_{i,jp}$ $-jp$ in the numbered line λ_i a linguistic term that gives the value of a variable;

w_{jp} - rule weight coefficient with sequence number jp;

$z_s(\lambda) = z_s(\lambda*)$ - fuzzy rule inference.

Ψ we consider size to be a linguistic variable that can take values ranging from "Very-Very Low" to "High". Ψ the kernel of the fuzzy variable we denote as $\dot{\Psi}$ [13-15], therefore Ψ the value of the variable is "Very-Very Bad" corresponds to $\dot{\Psi} = 1$, and the value "Excellent" corresponds to- $\dot{\Psi} = l$.

$$\max_{\Lambda} \dot{\Psi}(\Lambda) = \dot{\Psi}(\Lambda) = \dot{\Psi}^{\bullet}, \qquad (3)$$
$$\Lambda \in D_{\Lambda}.$$

Every incoming variable Ψ_{jp} will have its own relevance function with a fuzzy term.

Ψ_{jp} having term λ_i membership function of the element is as follows:

$$\mu^{jp}(\lambda_i) = \frac{1}{1 + \left(\dfrac{\lambda_i - b_i^{jp}}{c_i^{jp}}\right)^2},$$

here b_i^{jp}, c_i^{jp} - parameters of relevance functions.

Sugeno model of multicriteria optimization problem.

If $\lambda_1^1 = L$ and $\lambda_2^1 = L$ ва $\lambda_3^1 = H$ **or** $\lambda_1^1 = L$ and $\lambda_2^1 = ML$ and $\lambda_3^1 = H$ **or** $\lambda_1^1 = L$ and $\lambda_2^1 = M$ and $\lambda_3^1 = M$ **or** $\lambda_1^1 = L$ and $\lambda_2^1 = H$ and $\lambda_3^1 = ML$ **or** $\lambda_1^1 = L$ and $\lambda_2^1 = H$ and $\lambda_3^1 = L$ then

$$z = 14,06 + 0,0001\frac{\sum_{j=1}^{n}\mu(\lambda_1^{1j})\lambda_1^{1j}}{\sum_{j=1}^{n}\mu(\lambda_1^{1j})} - 2,9\frac{\sum_{j=1}^{n}\mu(\lambda_2^{1j})\lambda_2^{1j}}{\sum_{j=1}^{n}\mu(\lambda_2^{1j})} + 0,0001\frac{\sum_{j=1}^{n}\mu(\lambda_3^{1j})\lambda_3^{1j}}{\sum_{j=1}^{n}\mu(\lambda_3^{1j})}.$$

If $\lambda_1^1 = ML$ and $\lambda_2^1 = L$ and $\lambda_3^1 = H$ **or** $\lambda_1^1 = M\Pi$ and $\lambda_2^1 = M\Pi$ and $\lambda_3^1 = M$ **or** $\lambda_1^1 = M\Pi$ and $\lambda_2^1 = M$ and $\lambda_3^1 = M\Pi$ **or** $\lambda_1^1 = M\Pi$ and $\lambda_2^1 = H$ and $\lambda_3^1 = L$ then

$$z = 21,25 + 0,0001\frac{\sum_{j=1}^{n}\mu(\lambda_1^{1j})\lambda_1^{1j}}{\sum_{j=1}^{n}\mu(\lambda_1^{1j})} - 4,0001\frac{\sum_{j=1}^{n}\mu(\lambda_2^{1j})\lambda_2^{1j}}{\sum_{j=1}^{n}\mu(\lambda_2^{1j})} + 0,0001\frac{\sum_{j=1}^{n}\mu(\lambda_3^{1j})\lambda_3^{1j}}{\sum_{j=1}^{n}\mu(\lambda_3^{1j})}.$$

If $\lambda_1^1 = M$ and $\lambda_2^1 = L$ and $\lambda_3^1 = M$ **or** $\lambda_1^1 = M$ and $\lambda_2^1 = M$ and $\lambda_3^1 = L$ **or** $\lambda_1^1 = H$ and $\lambda_2^1 = L$ and $\lambda_3^1 = ML$ **or** $\lambda_1^1 = H$ and $\lambda_2^1 = ML$ and $\lambda_3^1 = L$ **or** $\lambda_1^1 = H$ and $\lambda_2^1 = L$ and $\lambda_3^1 = L$ then

$$z = -14.0 + 70,5\frac{\sum_{j=1}^{n}\mu(\lambda_1^{1j})\lambda_1^{1j}}{\sum_{j=1}^{n}\mu(\lambda_1^{1j})} - 4,0\frac{\sum_{j=1}^{n}\mu(\lambda_2^{1j})\lambda_2^{1j}}{\sum_{j=1}^{n}\mu(\lambda_2^{1j})} + 0,0001\left[\frac{\sum_{j=1}^{n}\mu(\lambda_3^{1j})\lambda_3^{1j}}{\sum_{j=1}^{n}\mu(\lambda_3^{1j})}\right]^2.$$

The problem of multi-criteria optimization of weakly formed processes can be solved based on the construction of the Sugeno fuzzy logic model.

CONCLUSION

This research has undertaken a comprehensive examination of the classification of loosely structured processes, emphasizing analytical analysis and the development of structural frameworks, as well as educational resources. It has been demonstrated that addressing the contemporary challenge of modeling slow-forming processes, especially when confronted with ambiguous data, necessitates specialized methods and mathematical techniques from the field of fuzzy set theory. Furthermore, an algorithm has been devised for tackling the multi-criteria optimization challenge within these loosely structured processes, employing a fuzzy logic model as its foundation. This approach has enabled the effective resolution of multi-criteria optimization challenges pertaining to the optimal deployment of firefighting units at designated positions.

In addition, improvements have been made to the algorithm for constructing Mamdani neurofuzzy models based on matrix representations of fuzzy logic. The solution to the problem of classifying such loosely structured processes has been instrumental in the creation of a comprehensive software package. The culmination of this research represents a significant advancement in the realm of modeling and optimizing complex processes, offering practical solutions and tools that can be applied across various domains, including firefighting and beyond. Ultimately, the findings and methodologies presented herein offer a promising avenue for improving decision-making processes in firefighting management. They provide a robust foundation for future research and practical applications aimed at bolstering the safety and effectiveness of firefighting operations.

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