Mathematical Model of Integral Fire Risk Management

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Abstract. In the given work the analysis of features of mathematical model of management of integral fire risk is carried out, and also grouping of administrative-territorial units of Ukraine on level of integral fire risk by means of the cluster analysis is carried out. As a result of the analysis, all regions of Ukraine were divided into 4 groups. This will allow to apply an appropriate model of integral fire risk management for each group. Further research will be aimed at developing a method of integral fire risk management, which is expected to be applied to each group of regions.

Keywords: Mathematical Model, Fire Risk, Clustering, Correlation Analysis.

1 Introduction

At present, the actual scientific and applied problem is the development of effective models of integral fire risk management. An example of these tasks is the minimization of the risk for a person to die as a result of dangerous events (natural and man-made events, fires, etc.).

The integral risk characterizes the consequences of dangerous events. One of the ways to minimize its level is the creation of rescue units (RUs). This approach is in line with the Strategy for Reforming the Civil Service of Ukraine in Emergencies [1], as the response time to dangerous events in rural areas can reach even one hour. Thus, the development of models and methods of integral fire risk management is relevant and will help solve the above problem.

Modern methods for determining the integral risks of dangerous events are given, for example, in [2, 3]. In works [4, 5] the analysis of integral fire risks on the territory of Ukraine is carried out and grouping of administrative-territorial units according to risk levels by means of the cluster analysis is carried out. Mathematical model of integral fire risk management and its features are given in [6]. The development of models and methods of optimal coverage of given areas by geometric objects with variable metric characteristics is devoted to [7], but this study did not take into account the need to cover discrete elements of these areas.

In this paper, it is necessary to develop a mathematical model of management of the integral fire risk.

2 Presentation of the main research material

Consider the construction of a mathematical model of integral fire risk management. In one of the previous works [8] it was concluded that the integral fire risk depends on the average time of RUs to arrival to the emergency location. At the same time, it is necessary to take into account the impact of the distribution of rescue units on their average travel time to the place of call and assess the impact of the standard time of arrival of rescue units (RUs)to the place of departure of these units.

It was assumed that the average time of RUs to the place of occurrence of the dangerous event and, as a consequence, the average time of localization and elimination of the dangerous event depend on the coverage of the respective territory by the areas of departure of RUs. The specified coefficient is calculated using the following expression:

$$k_{\text{cover}} = \frac{S\left(\bigcup_{q=1}^{N_q} P_q\right)}{S(S_0)}, \tag{1}$$

where N_q – the number of existing RUs; P_q – area of departure q -th unit ; S_0 – given territory; $S(.)$ – area calculation function.

As an example, Figure 1 shows the dependence of the average time of RUs to the place of call on the coverage factor for the Kharkiv region, as well as calculated the correlation coefficient and constructed a trend line using the method of least squares. To conduct the study, software was developed in the Java programming language in the IntelliJ IDEA environment using the JavaFX library.

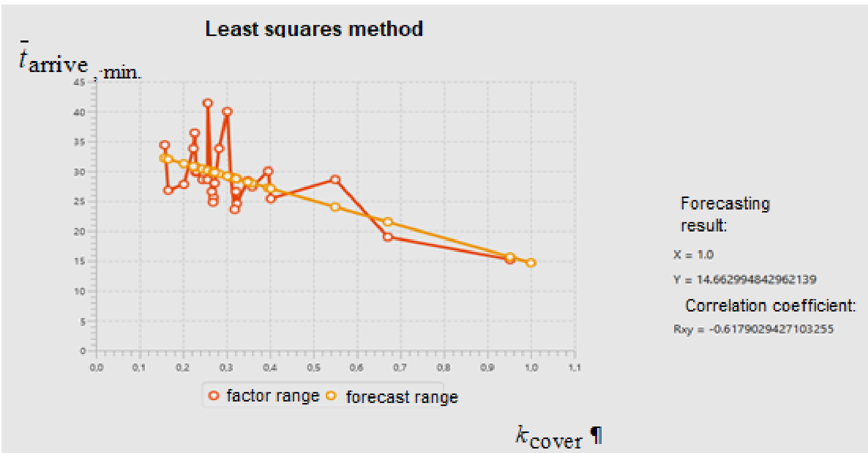

Fig. 1. Dependence of the average travel time to a dangerous event on the coverage factor for the Kharkiv region.

It can be concluded that between the average travel time of rescue units to the scene of an emergency (dangerous event) and the coverage ratio of these units in the Kharkiv region there is an inverse correlation (correlation coefficient is -0.62), and the regression equation the following view:

$$\bar{\tau}_{arrive} = -20,799 \cdot k_{cover} + 35,46. \quad (2)$$

In expression (2) the coefficient at k_{cover} and the free term are measured in minutes. Similar dependencies can be obtained for other administrative-territorial units of Ukraine.

Thus, the following problem arises. Let a certain administrative-territorial unit S_0 be given in the form of a polygon in the global coordinate system (Fig. 2). The region S_0 has discrete elements V_k, $k = 1,\ldots,N_k$, which are settlements. Let $G_l \subset V_k$, $l = 1,\ldots,L$, $L < N_k$, – united territorial communities (settlements), in which it is permissible to create operational and rescue units in accordance with [9, 10].

The settlements in which (next to which) there are potentially dangerous objects and / or objects of the increased danger, we will designate through $S_d \subset G_l$, $d = 1,\ldots,D$, $D < L$ (the specified objects can become factors of realization of technogenic risks).

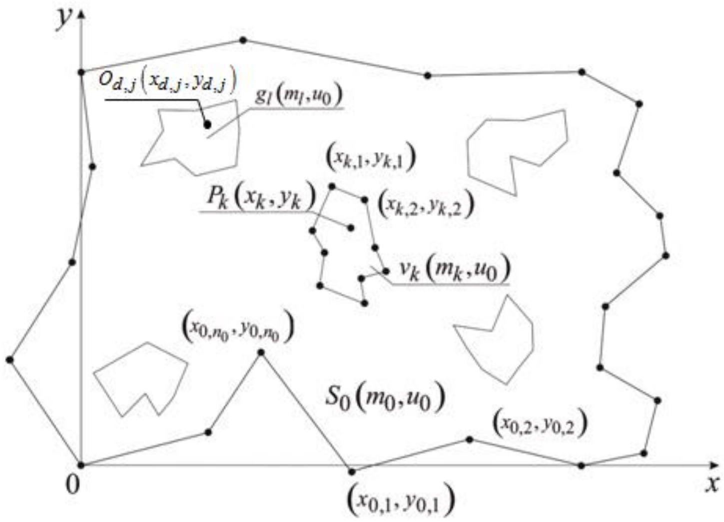

Fig. 2. The region $S_0(m_0, u_0)$ with distrete elements $v_k(m_k, u_0)$, $k = 1,\ldots,N_k$, and $g_l(m_l, u_0)$, $l = 1,\ldots,N_l$.

It is necessary to cover the area S_0 with the exit areas of rescue units P_i, $i = 1,\ldots,N$ with the exit areas of rescue units

– minimum area of crossing of exit areas of operative-rescue divisions;

– belonging of departure areas of operative-rescue divisions of area S_0;
– affiliation of settlements V_k, $k = 1,\ldots,N_k$, as well as settlements S_d, $d = 1,\ldots,D$ areas of departure of operational and rescue units (taking into account other integral risks of emergencies and hazards of man-made nature);
– the travel time of rescue units to the most remote point of the departure area P_i, $i = 1,\ldots,N$ should not exceed the specified T^* (in cities – 10 minutes; in settlements outside the city – 20 minutes [8, 9]);
– placement of operational and rescue units is carried out in the united territorial communities (settlements) G_l, $l = 1,\ldots,L$;
– minimum number of operational and rescue units P_i, $i = 1,\ldots,N$.

The mathematical model of distribution of operational and rescue units according to the level of integral risk of emergencies and dangerous events of man-caused nature is as follows [11]:

$$\min_{u \in W} R_3\left(\bar{\tau}_{arrive}, \bar{\tau}_{loc}, \bar{\tau}_{liq}, N_{fire}\right);\ u = \{m_i; v_i\};\ i = 1,\ldots,N, \tag{3}$$

where W:

$$\omega\left(m_i, m_j, v_i, v_j\right) \to \min \tag{4}$$

$$i = 1,\ldots,N;\ j = i+1,\ldots,N;$$

$$\omega\left(m_i, m_{cS_0}, v_i, v_{cS_0}\right) \to \min \tag{5}$$

$$i = 1,\ldots,N;\ S_0 \bigcup cS_0 = R^2$$

$$V_k \in \{P_i\};\ k \in \{1,\ldots,N_k\};\ i = 1,\ldots,N; \tag{6}$$

$$S_d \in \{P_i\};\ d = 1,\ldots,D;\ i \in \{1,\ldots,N\}; \tag{7}$$

$$\bar{\tau}_{arrive}\left(P_i\right) \le T^*;\ i = 1,\ldots,N; \tag{8}$$

$$\bar{\tau}_{arrive} = f\left(k_{cover}\right); \tag{9}$$

$$u = \{m_i; v_i\} \in \{G_l\};\ G_l \in \{P_i\};\ i = 1,\ldots,N;\ l = 1,\ldots,L; \tag{10}$$

$$N \to \min. \tag{11}$$

In order to assess the negative effects of each type of emergencies of technogenic character, the integral risks of these emergencies were calculated in accordance with the expression (3). The graphic interpretation of integral risks is shown in Fig. 2, with the highest levels corresponding to the integral risk of emergencies due to fires and explosions, $2,95 \cdot 10^{-6}$ 1/year, and the integral risk of emergencies due to accidents and vehicle accidents (except for fires and explosions) $1,98 \cdot 10^{-6}$ 1/year. The levels of integral risks of other types of emergencies are less than one order (several orders of magnitude) of the above-mentioned risks.

It should be n oted that the analysis of only integral risks of emergencies of technogenic character for the estimation of the level of technogenic safety in the territory of Ukraine is not sufficiently informative as it does not take into account hazardous events that are not classified. In the mathematical model (3)÷(11) expression (3) is the objective function of the problem, with m_i – the coordinates of the vertices of polygons P_i, $i = 1, \ldots, N$ in the local coordinate system, v_i – the parameters of the location of objects P_i (the position of the local coordinate system of the i -th object in the global coordinate system); expression (4) – is a condition of the minimum of mutual intersection of objects P_i and P_j, where is a $\omega(.)$ – ω- function, which is the area of intersection of polygons P_i and P_j; expression (5) – the condition of the minimum intersection of objects P_i with the addition of the region S_0 to the Euclidean space R^2 ; expression (6) – condition of belonging of settlements V_k, $k = 1, \ldots, N_k$ areas of departure of RUs P_i; expression (7) – condition of belonging of settlements S_d, $d = 1, \ldots, D$ areas of departure of RUs P_i; expression (8) – a condition regarding the arrive time of RUs to the place of call; expression (9) – the relationship between the average arrive time of RUs and the coverage ratio of the region S_0; expression (10) – the condition of placement of RUs in the united territorial communities (settlements) G_l, $l = 1, \ldots, L$; expression (11) – is a condition of the minimum number of RUs.

Administrative-territorial units of Ukraine have features that must be taken into account when developing a mathematical model of the distribution of RUs according to the level of integral risk of emergencies and dangerous events. To do this, we will group the regions of Ukraine by the level of integral fire risk (the main criterion in minimizing the consequences of emergencies and dangerous events) and build regression models that describe the relationship of integral risk with the main factors for each cluster.

The main purpose of cluster analysis [12] is to divide the set of studied objects and features into homogeneous in the appropriate sense of the group or cluster. This means that the task of classifying data and identifying the appropriate structure in it is solved. Methods of cluster analysis can be used in a variety of cases, even in cases where it is a simple grouping, in which it all comes down to the formation of groups by quantitative similarity.

Taking into account the statistics on deaths due to fires and explosions for the last 7 years [13–19], we calculate the integral fire risk [4] and process the results using the software STATISTICA 10. It should be noted that the estimated data do not contain data on the Autonomous Republic of Crimea, Donetsk and Luhansk regions due to the impossibility of obtaining complete statistical information on dangerous events (fires and explosions) in the temporarily occupied territories of Ukraine.

There are two main classifications of clustering algorithms:

1. Hierarchical and non-hierarchical (flat). Hierarchical algorithms build a system of nested partitions, ie at the output of the algorithm is a tree of clusters, with the root as the whole sample and the leaves - as the smallest clusters. Non-hierarchical algorithms build only one division of objects into clusters.
2. Clear and indistinct. Clear algorithms give all sample objects the appropriate cluster number, which means that each object must belong to only one cluster. Fuzzy algorithms assign a set of values to each object, which demonstrates the degree to which the object belongs to the clusters. Therefore, each object belongs to each cluster with a certain probability.

We will carry out clustering by a hierarchical method. Hierarchical method - tree clustering. Hierarchical algorithms are based on the idea of sequential clustering. Initially, each object is considered as a separate cluster. In the next step, some of the closest clusters will be merged into a separate cluster.

Using the hierarchical method of cluster analysis, we will divide the administrative-territorial units of Ukraine into groups (Figure 3), which will be characterized by a similar situation with regard to deaths due to fires or explosions per unit time.

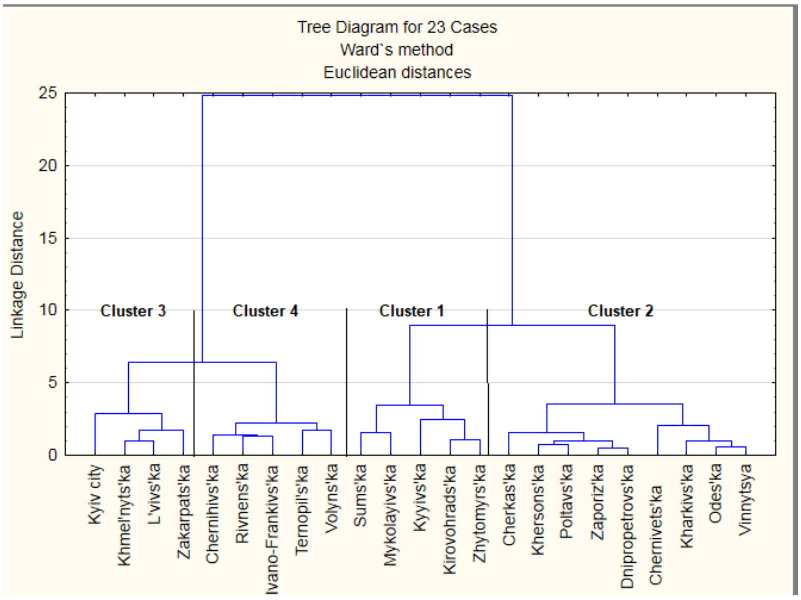

Fig. 3. Vertical tree dendrogram by the Ward method, which shows the distance of the union of the studied areas.

Finally, we take the number of clusters equal to 4, because in the case of a further increase in their number, the clarity of classification is lost.

Table 1. Information on the grouping of administrative-territorial units of Ukraine by the number of clusters, which is equal to 4 (K=4).

Groups of clusters at K=4	Regions of Ukraine and Kyiv city	Linkage distance
Cluster 1	Sums′ka, Mykolayivs′ka, Kyyivs′ka, Kirovohrads′ka ta Zhytomyrs′ka regions	8,352732
Cluster 2	Chernivets′ka, Khersons′ka, Poltavs′ka, Zaporiz′ka, Dnipropetrovs′ka, Cherkas′ka, Kharkivs′ka, Odes′ka ta Vinnyts′ka regions	7,410969
Cluster 3	Kyiv city, Khmel′nyts′ka, L′vivs′ka, Zakarpat·s′ka regions	7,20112
Cluster 4	Chernihivs′ka, Rivnens′ka, Ivano-Frankivs′ka, Ternopil′s′ka ta Volyns′ka regions	4,466044

Consider the construction of regression models to determine the integral risk of emergencies and dangerous events in groups of administrative-territorial units of Ukraine. These models will allow to obtain the dependences of integral fire risks (the main criterion in the task of minimizing the consequences of emergencies and dangerous events) on the main factors that characterize the response process of RUs for each cluster. To do this, we apply correlation-regression analysis, and assume that the dependences are linear. We will also check the obtained coefficients of linear models for reliability and adequacy.

First of all, let's establish the links between the integral fire risk and the factors that affect it for each cluster (Tables 2–5). The analysis of the data given in Tables 2–5 allows us to conclude that the risk is directly proportional to the number of deaths, so for further analysis this factor must be excluded from the calculation (correlation matrix coefficients will not change). In each of the matrices you can see the inverse dependence of risk on the number of dangerous events, based on available statistics. In the first and second clusters (Tables 2 and 3) - the inverse dependence of risk on the average elimination time. Most correlation coefficients exceed 0.7, which indicates a strong relationship between the studied parameters.

Table 2. Correlation matrix of the main factors influencing the integral fire risk R_3 for the first cluster.

Variable	Correlations (cluster 1)					
	N_{fire}	$N_{victims}$	$\bar{\tau}_{arrive}$	$\bar{\tau}_{loc}$	$\bar{\tau}_{liq}$	R_3
N_{fire}	1,00	-0,85	-0,34	-0,45	-0,65	-0,85
$N_{victims}$	-0,85	1,00	0,64	0,70	0,82	1,00
$\bar{\tau}_{arrive}$	-0,34	0,64	1,00	0,96	0,94	0,64
$\bar{\tau}_{loc}$	-0,45	0,70	0,96	1,00	0,96	0,70
$\bar{\tau}_{liq}$	-0,65	0,82	0,94	0,96	1,00	0,82
R_3	-0,85	1,00	0,64	0,70	0,82	1,00

Table 3. Correlation matrix of the main factors influencing the integral fire risk R_3 for the second cluster.

Variable	Correlations (cluster 2)					
	N_{fire}	$N_{victims}$	$\bar{\tau}_{arrive}$	$\bar{\tau}_{loc}$	$\bar{\tau}_{liq}$	R_3
N_{fire}	1,00	-0,89	-0,79	-0,63	0,36	-0,89
$N_{victims}$	-0,89	1,00	0,84	0,82	-0,45	1,00
$\bar{\tau}_{arrive}$	-0,79	0,84	1,00	0,81	-0,13	0,84
$\bar{\tau}_{loc}$	-0,63	0,82	0,81	1,00	0,23	0,82
$\bar{\tau}_{liq}$	0,36	-0,45	-0,13	0,23	1,00	-0,04
R_3	-0,89	1,00	0,84	0,82	-0,04	1,00

Table 4. Correlation matrix of the main factors influencing the integral fire risk R_3 for the third cluster.

Variable	Correlations (cluster 3)					
	N_{fire}	$N_{victims}$	$\bar{\tau}_{arrive}$	$\bar{\tau}_{loc}$	$\bar{\tau}_{liq}$	R_3
N_{fire}	1,00	-0,60	-0,69	0,08	0,10	-0,60
$N_{victims}$	-0,60	1,00	0,83	0,22	0,08	1,00
$\bar{\tau}_{arrive}$	-0,69	0,83	1,00	-0,10	0,15	0,83
$\bar{\tau}_{loc}$	0,08	0,22	-0,10	1,00	-0,83	0,22
$\bar{\tau}_{liq}$	0,10	0,08	0,15	-0,83	1,00	0,08
R_3	-0,60	1,00	0,83	0,22	0,08	1,00

Table 5. Correlation matrix of the main factors influencing the integral fire risk R_3 for the fourth cluster.

Variable	Correlations (cluster 4)					
	N_{fire}	$N_{victims}$	$\bar{\tau}_{arrive}$	$\bar{\tau}_{loc}$	$\bar{\tau}_{liq}$	R_3
N_{fire}	1,00	-0,70	-0,51	-0,84	0,46	0,70
$N_{victims}$	-0,70	1,00	0,86	0,88	0,74	1,00
$\bar{\tau}_{arrive}$	-0,51	0,86	1,00	0,75	0,88	0,86
$\bar{\tau}_{loc}$	-0,84	0,88	0,75	1,00	0,88	0,86
$\bar{\tau}_{liq}$	0,46	0,74	0,88	0,78	1,00	0,74
R_3	0,70	1,00	0,86	0,88	0,74	1,00

After conducting a correlation-regression analysis and identifying significant factors and their values for each cluster, we obtain the following regression models to determine the integral fire risk in groups of administrative-territorial units of Ukraine:

$$R_3^1 = \left(5,878 + 0,199\bar{\tau}_{arrive} - 0,87 \cdot 10^{-4} N_{fire} + \varepsilon\right) \cdot 10^{-5}; \quad (12)$$

$$R_3^2 = \left(0,646\bar{\tau}_{arrive} - 0,74 \cdot 10^{-4} N_{fire} + \varepsilon\right) \cdot 10^{-5}; \quad (13)$$

$$R_3^3 = \left(-5,335 + 0,16\bar{\tau}_{arrire} + 0,212\bar{\tau}_{loc} + 0,166\bar{\tau}_{liq} - \right.$$

$$\left. -0,9 \cdot 10^{-4} N_{fire} + \varepsilon\right) \cdot 10^{-5}; \quad (14)$$

$$R_3^4 = \left(-3,123 + 0,274\bar{\tau}_{arrive} + 0,273\bar{\tau}_{loc} + \varepsilon\right) \cdot 10^{-5}; \quad (15)$$

The standard error of evaluation of the obtained results is less than 5%.

Thus, with the help of correlation-regression analysis, regression models were obtained to determine the integral fire risk in groups of administrative-territorial units of Ukraine. These models allowed to obtain the dependences of these risks on the main factors that characterize the response process of RUs for each cluster, and are also the basis for building models of distribution of RUs by the level of integral risk.

Consider the features of the mathematical model (3) ÷ (11):

1. The objective function of the problem is an expression of the form (12) ÷ (15) depending on which cluster the administrative-territorial unit (coverage area) belongs to.
2. In the case of taking into account the locations of existing RUs, the following restriction must be added to the mathematical modelr:

$$\omega\left(m_i, m_q, v_i, v_q\right) \to \min; \quad i = 1,\ldots,N; \quad q = 1,\ldots,N_q \quad (16)$$

where N_q – the number of existing RUs.

3. If the problem of minimizing the consequences of emergencies by dividing the RUs by the level of integral risk of emergencies and dangerous events is solved taking into account the limited resources, then in the mathematical model instead of constraint (11) it is necessary to use the following expression:

$$Q_{res}(N) \le Q_{res}^{*} \quad (17)$$

where $Q_{res}(N)$ – resources needed to create N RUs; Q_{res}^{*} – resources allocated for the creation of RUs.

4. The objective function of the problem is linear, the constraints are linear, nonlinear and discrete.

5. The type of RUs is determined depending on the objects of protection located in the service area.

Thus, a mathematical model of integral fire risk management is developed and its features are investigated. The target function is the dependence of the integral fire risk on the main factors that characterize the process of response to RUs. The distribution of RUs is carried out taking into account: the normalized response time to emergencies (dangerous events); belonging of high-risk objects and potentially dangerous objects to the areas of departure of units (taking into account other integral risks of emergencies and dangerous events); placement of PDOs in united territorial communities (certain settlements).

3 Conclusions

In this paper the analysis of features of mathematical model of management of integral fire risk is carried out, and also grouping of administrative-territorial units of Ukraine on level of integral fire risk by means of the cluster analysis is carried out. As a result of the analysis, all regions of Ukraine were divided into 4 groups. This will allow to apply an appropriate model of integral fire risk management for each group. Further research will be aimed at developing a method of integral fire risk management, which is expected to be applied to each group of regions.

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