

Проведено дослідження процесу реагування аварійно-рятувальних формувань на надзвичайні ситуації та небезпечні події, які виникають на території міста з населенням понад один мільйон осіб. Встановлено, що потік викликів, які надходять до підрозділів аварійно-рятувальних формувань, має певну структуру і їх чисельність корелює з показником загальної площі житлового фонду населеного пункту. Названа залежність була описана поліноміальною лінією тренду для якої було складено відповідне рівняння, яке дозволяє визначити чисельність викликів, які можуть надходити у майбутньому до підрозділів аварійно-рятувальних формувань. Ці дані можуть бути також використані для визначення чисельності оперативних транспортних засобів, якими повинні бути забезпечені підрозділи аварійно-рятувальних формувань для ефективного проведення ними дій за призначенням. Запропоновано метод комплектування підрозділів аварійно-рятувальних формувань оперативними транспортними засобами з урахуванням оперативної обстановки в їх районах виїзду, який полягає у виконанні чотирьох послідовних етапів. Перший етап передбачає проведення відбору необхідних показників на основі аналізу статистичних даних, які характеризують процес реагування підрозділів аварійно-рятувальних формувань на різного роду деструктивні події, та побудову прогностичної моделі. Другий етап передбачає проведення розрахунку показника приведеної чисельності автомобілів на виклик з урахуванням різних груп потоків викликів. Третій етап передбачає визначення загальної чисельності оперативних транспортних засобів для аварійно-рятувальних формувань населеного пункту. У зв'язку з тим, що на цьому етапі використовуються математичні моделі, які ґрунтуються на законі розподілу Пуассона, то існує обмеження при використанні запропонованого методу, яке полягає у тому, що потік викликів повинен бути пуассонівським. Четвертий етап розрахунків передбачає перерозподіл раніше визначеної загальної чисельності оперативних транспортних засобів по підрозділам аварійно-рятувальних формувань з урахуванням особливостей оперативної обстановки в їх районах виїзду

Ключові слова: аварійно-рятувальне формування, потік викликів, методика комплектування, оперативний транспортний засіб

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1. Introduction

One of the important functions of a state is to protect the population from hazards and emergencies that occur on its

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DEVELOPMENT OF A METHOD OF COMPLETING EMERGENCY RESCUE UNITS WITH EMERGENCY VEHICLES

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territory. To fulfil this function, three main aspects can be distinguished, namely prevention, response and assistance in cases of hazards and emergencies affecting the population. Prevention involves undertaking preventive measures to

reduce the likelihood of various destructive events. In addition, this direction helps reduce the level of a negative impact from destructive events, both in buildings and structures as well as in natural ecosystems, due to their early detection and restriction of their spread. The process of responding to hazards and emergencies involves their localization and elimination by emergency rescue units (ERUs) by carrying out fire fighting and rescue operations for various purposes.

The success of the ERU operational activities depends mainly on the time of concentrating the forces and means at the place of a call, as well as their numerical strength, level of training, and equipment. In many cities around the world, it often takes more than 10 minutes to bring the ERU forces and resources. The stated time value exceeds similar indices in the developed countries of the world and is the reason of the considerable increase of the scale of hazards and emergencies at the moment of the units' arrival. This problem is mainly related to the peculiarities of the deployment of forces and means of an ERU and their numerical composition, which does not always correspond to the nature of the operational situation existing in the territory of the respective settlements. The solution to this problem is seen in the re-deployment of the available forces and means of the ERU and, if necessary, the adding other necessary resources, taking into account the existing operational environment, which requires the use of well-grounded methods.

2. Literature review and problem statement

In determining a city's needs for ERUs in terms of forces and means, their equipment, locations, and the list of the objective functions they perform, a number of different factors should be considered. In [1], it is found that the number of emergency vehicles (EVs) in settlements is determined on the basis of the regulatory approach. The main factors that are taken into account are the population size and the number of storeys in buildings of a respective settlement. In the process of determining the number of EVs for ERUs, the regional features (climate and terrain) and the nature of the settlement development are not taken into account. In [2], a systematic approach is suggested to assess the readiness of the ERU forces and means to conduct operational activities. The approach proposed in [2] takes into account the probability of failure-free operation of the technical means as well as the level of professional training and the extent of the unit completeness. In [3], it is proposed to use a similar approach as in [2] when assessing ERUs' readiness for the intended purpose. The goal of this assessment is to solve the tasks of establishing the order of the departments of ERUs for completing them with new EVs. The assessment is performed by two criteria: the operational readiness of the departments before and after completing them and the technical readiness of the departments before and after completing them. Accordingly, the methods proposed in [2, 3] are intended to assess the readiness of the departments to perform the purpose, taking into account the existing EV fleet. These methods do not allow determining the required number of special technical means for completing an ERU.

In [4], a technique is proposed to evaluate the performance of fire departments, which entails presenting fire statistics as a vector in a six-dimensional Euclidean space. The results of this evaluation can be used to classify and group objects by the level of similarity in the specifics of the

operational activities of ERUs, which requires the presence of a certain set of everything necessary at the maintenance point. In the process of grouping objects by this criterion, a statistical distribution similar to the Pareto distribution is obtained. Accordingly, this study also suggests the use of an ABC analysis based on the Pareto distribution to estimate an ERU's need for EVs. In [5], using the ABC analysis, areas are ranked according to the intensity of occurrence of hazards and emergencies in them. The conducted ranking simplifies the task of monitoring hazards and emergencies in a respective territory and allows for a more efficient distribution of ERU forces and means among the departments. In [6], for the purpose of grouping EVs by the frequency of use in the process of conducting operational activities by ERU departments, the ABC analysis is performed. In the process of the ABC analysis, it is a significant problem to set the classification boundaries of the groups A, B, and C. The classification limits of the groups A, B, and C are set either in accordance with the Pareto Law, or graphical method, or using the peer review method. Accordingly, the results obtained when grouping EVs by the frequency of use are often subjective.

In [7], methods are proposed for determining the location of ERU departments on the territory of a settlement, which influences the time of their response to hazards and emergencies. The location of the departments is determined based on sixty-one criteria. The optimal location of the departments is selected from several alternatives that help determine the appropriate methods. A similar problem can be solved by the methods proposed in [8]. These methods, in contrast to the methods proposed in [7], also take into account the peculiarities of completing ERU departments with various types of EVs. Accordingly, the considered methods [7, 8] help determine the locations of ERU departments in the territory of a settlement, taking into account the minimum time of their arrival at the place of call. The time of arrival from the ERU department location to the place of a call can be estimated by the method proposed in [9]. In determining the average time of arrival at the place of a call, certain characteristics of the street-road network of the settlement are taken into account. Using the method of [9], it is possible to determine the time of the ERU arrival at the places of liquidating hazards and emergencies, depending on the type of the EVs at the disposal of the unit. In [10], the determination of the required sites of ERU concentration is proposed to be performed by a geospatial analysis. The method of geospatial analysis helps establish the dependence of the number of calls to an ERU department on factors such as, for example, the social status of the population and the number of storeys in the buildings of the respective administrative territory of a settlement. With the predicted value of the number of calls in a particular area, it is possible to set the required number of EVs for ERUs engaged in their maintenance.

In [11], mathematical models are suggested for estimating the probability of ERUs' refusal to service a call due to the employment of forces and means to service another call. The mathematical models can be introduced into the ERU dispatching service with the purpose of early redistribution of forces and means on the territory of the settlement, depending on a change of the operational situation. However, it is possible to obtain only a relative estimate of the probability of refusing to service a call, on the basis of which it is quite difficult to determine the required number of the ERU forces and resources.

In [12], the researchers propose a method for determining the required types and quantities of EVs for ERUs of industrial parks and conduct simulation modelling. The mathematical models that are part of the algorithm used by the researchers in the simulation system are based on the assumption that the call flows are stationary Poisson, and the time spent by the vehicles on servicing a call is described by the exponential distribution law. The problem with using this method is the need to calculate all the probable values of the empirical frequency of using the EVs on calls, which is not always possible in practice. Accordingly, addressing the problem requires a number of assumptions, which produces errors in the results of the research and therefore reduces their accuracy.

The flow of calls coming to the ERUs of settlements is characterized by unevenness, in particular daily [13]. This unevenness is the reason that depending on the time of day in certain areas of the settlement there is a rapid increase in the number of calls, in some cases several times. In these instances, the forces and means of the ERUs that are concentrated in these territories are not sufficient for effective operational activities. In [14], statistical regularities that characterize the flow of calls to the ERUs of cities with a population of more than one million are tested. According to the results of these tests, it is established that the flow of calls is Poisson. Consequently, this makes it possible to use mathematical models based on the Poisson distribution law to describe the process of calls coming to the ERUs. The method proposed in [15] is designed to solve the problem of redistribution of forces and means, provided that the operational situation in the territory of a settlement changes. The specified method cannot be used to determine the required number of EVs in ERUs.

Systems to support decision-making can be used to determine the required types and quantitative composition of ERU forces and resources when sending them for operational activities. These systems are created using different scientific approaches [16]. Recommendations for the development of information systems are given in [16] to determine the approximate required number of forces and means to be sent to operational sites. In the tests of [17], an approach is proposed to determine the required number of forces and means in order to send them to the place of a call based on neural network prediction methods. According to [18], the method of neural network prediction has a number of significant disadvantages that denote the complexity of its use in the activities of ERUs. These disadvantages are related to the stochastic nature of the flow of calls to an ERU. Accordingly, the methods and approaches proposed in [16, 17] are narrowly directed and developed with the purpose of solving the problem, which is to establish the required number of personnel and EVs to be sent to the place of eliminating hazards and emergencies arising on the territory of a settlement.

In [19], a method is proposed to determine the required number of EVs for ERUs, taking into account statistics that reflect the number of special vehicles involved by type into the process of servicing calls in a settlement. This method helps determine the number of container vehicles and carrier vehicles, that is, designed for a specific category of special equipment that is not yet in the equipment set of any of the ERUs of Ukraine.

Thus, the methods and approaches discussed are narrowly focused and help solve specific problems. Among

these tasks are the identification of the locations of the units, the assessment of the level of readiness of the forces and means to perform target actions, and the establishment of their required number. Most of the known methods make it possible to determine the number of EVs in ERUs only at the stage of designing settlements. In the process of determining the types and number of EVs for ERUs, the population and the nature of the development of a respective settlement are taken into account. A settlement may change in the size of its population and the nature of its development, which influences the effectiveness of the response to hazards and emergencies by its ERU(s). Known mathematical models that are part of the methods for determining the number of EVs in ERUs are predominantly based on the Poisson distribution law. Accordingly, it has been found that these models are used to determine the number of EVs in ERUs of cities with a population of more than one million. This feature is explained by the fact that in cities with a population of more than one million the flow of calls is Poisson. Accordingly, among the methods analysed there are none that make it possible to solve the problem of technical completing of ERUs with new EVs taking into account their existing locations of work in order to improve the effectiveness of the ERU response to hazards and emergencies.

3. The aim and objectives of the study

The aim of the study is to develop a method of completing emergency rescue units with emergency vehicles in solving the problem of their technical equipment.

To achieve this aim, the following objectives are set and done:

- to develop a predictive model that will help determine the number of calls to units dealing with the elimination of hazards and emergencies in a settlement;
- to substantiate the method of equipping emergency rescue units with emergency vehicles theoretically, which would take into account the conditions of the operational situation in the territory of the settlement.

4. Development of a predictive model for determining the number of hazards and emergencies

According to the results of the literature review [1–19], it has been found that the known methods for determining the number of EVs with the purpose of equipping ERUs and redeploying the available forces and means are developed mainly for million-plus cities. Such cities are characterized by a higher population density than other types of settlements, which is why the happening of hazardous events and emergencies on their territories is accompanied by a large number of victims and casualties. This feature explains the highest priority in the development of these methods for groups of settlements with a population of more than one million. In addition, for these population groups, the call flow to ERUs is Poisson.

Accordingly, the city of Kharkiv (Ukraine) was selected as a settlement with a population of more than one million. In particular, the results of previous studies [14] for this city confirmed the hypothesis of the Poisson character of the flow of calls coming to the city ERUs.

The data required for the research were obtained from the Main Directorate of the State Emergency Service of Ukraine in Kharkiv Oblast. These data represent an array of daily reports for a year on the state of progress of the ERU operational activities in the whole region. From this array, data concerning the operational activities of the ERUs in the city of Kharkiv were selected. The data obtained contain information on the time, place and scale of the hazards and emergencies as well as the characteristics of the processes of their elimination.

In order to build a predictive model, a number of factors were selected from the statistical data set, which had an influence on the number of calls to the ERUs in the settlement. These factors included: population, area, population density, total living space (apartment buildings and suburban houses), number of houses 26.5 m high and above, number of high-risk sites, and number of potentially dangerous sites. The dependence of the number of calls to the ERUs on the above factors was checked by performing correlation analysis. Some of the factors were derived from each other, had strong correlation, and were subsequently removed. Factors that had weak correlation with the number of calls to the ERUs were not considered either. The results of the correlation analysis are given in Table 1. Thereafter, the proportion of calls (β_z) attributable to each department of the ERUs was determined. The results obtained are given in Table 2.

Table 1
A matrix of paired correlations (correlation of the number of calls to the ERUs and probable factors of influence)

Variable	Population, thousand people	Total area of the housing stock, thousand m ²	Number of calls to the ERUs
Population, thousand people	1	0.98	0.9
Total area of the housing stock, thousand m ²	0.82	1	0.91
Number of residential buildings 26.5 m high and above	0.75	0.85	0.74
Number of calls to the ERUs	0.9	0.91	1

Fig. 1 shows the dependence of the number of calls on the total area of the housing stock of the respective administrative district of Kharkiv.

The dependence obtained by using a Microsoft Excel 2007 spreadsheet was approximated by a polynomial trendline. The type of the trendline was chosen based on the calculated value of the coefficient of determination, which characterizes the degree of closeness of the specified line to the original data. Possible types of trendlines were also considered; they were exponential, linear, logarithmic, and power. Accordingly, the highest determination coefficient value of 0.9727 was obtained for the polynomial trendline. The resulting polynomial trendline is described by the corresponding regression equation (1):

$$Y_i = 57.056 \cdot X_i^2 - 147.77 \cdot X_i + 2208.6, \quad (1)$$

where Y_i is the predictive value of the number of calls to the ERUs to carry out operational activities on the elimination of hazards and emergencies of the respective i -th administrative territory of the city; X_i is the total area of the housing

stock of the respective i -th administrative territory of the city, thousand m².

Table 2
Data on the number of calls to the ERUs

Unit	Average number of calls per year	Standard deviation	Relation to the city district	Proportion of calls to a separate department from among the total number of calls (β_z)
SFRD-1	445	34	Shevchenkivskiy	0.4
SFRD-17	362	29		0.33
SFRD-32	295	21		0.27
SFRD-5	568	50	Moscowskiy	0.36
SFRD-18	709	26		0.46
SFRD-22	286	9		0.18
SFRD-9	602	27	Kyivskiy	0.64
SFRD-27	303	44		0.32
SFRD-36	37	12		0.04
SFRD-8	457	60	Industrialnyi	0.68
SFRD-25	218	22		0.32
SFRD-2	532	32	Slobidskiy	1
SFRD-11	506	48	Nemyshlianskiy	1
SFRD-4	322	31	Osnovyan-skiy	0.63
SFRD-41	189	18		0.37
SFRD-26	107	22	Novobavarskiy	0.43
SFRD-7	140	39		0.57
SFRD-6	318	47	Kholodnohirskiy	0.47
SFRD-3	358	14		0.53

By constructing a polynomial regression equation of a higher degree than the second one, an increase in the value of the coefficient of determination can be achieved. However, the high value of the coefficient of determination does not guarantee that the quality of the predictions made using the polynomial regression equation will be high. For example, when choosing the sixth degree polynomial regression equation, the value of the determination coefficient will be high, but the trendline will not adequately describe the original data. This feature is a disadvantage of predicting based on the constructed polynomial regression equation. In view of this, it was decided to choose the second-degree polynomial regression equation.

The proposed predictive model helps determine the number of calls to ERUs depending on the total housing area of the respective administrative territory of a city. In order to determine the estimated number of calls that can be received by each individual ERU, it is necessary to take into account the pre-calculated factor β_z . These calculations can be performed with formula (2):

$$y_z = Y_i \cdot \beta_z, \quad (2)$$

where y_z is the predicted value of the number of calls to the z -th department of an ERU of the corresponding i -th administrative territory of a city.

Fig. 1 shows that the trendline is growing, that is, the larger the housing stock of a respective administrative territory, the greater the factor of the number of calls to its ERU(s).

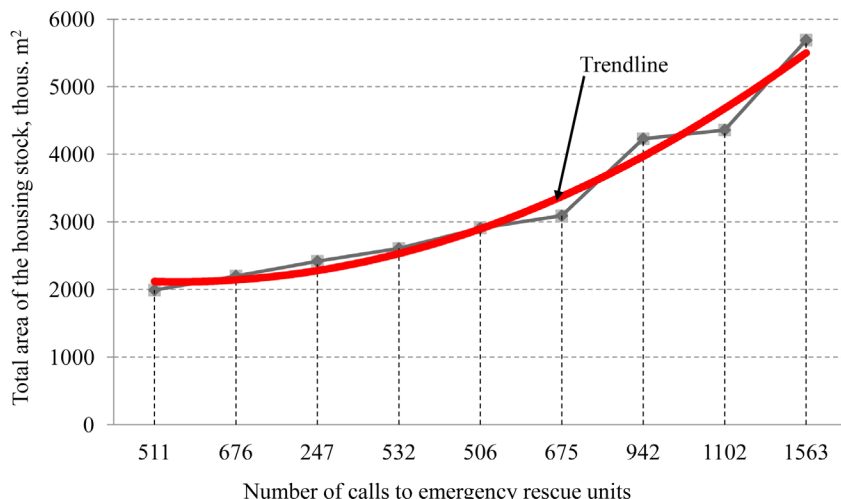


Fig. 1. Dependence of the number of calls on the total area of the housing stock of the respective administrative district of Kharkiv

5. Theoretical substantiation of the method of completing emergency rescue units with emergency vehicles

In order to determine the required number of various types of EVs, it is necessary to take into account the general structure of calls to the ERUs, which may differ slightly for diverse settlements. The fact is that, depending on the specifics of a call, various types of EVs are involved in conducting operational work. To determine the structure of calls to Kharkiv ERUs and to calculate the proportion of calls from their total number (γ_g), a corresponding study was conducted, and the results are given in Table 3.

Given the established structure of calls and having the predicted value of the total number of calls to the z-th department of the ERU, it is possible to determine the probable number of calls when the factor γ_g is calculated by the following calculation formula:

$$K_f = y_z \cdot \gamma_g, \tag{3}$$

where K_f is the probable number of calls to the z-th department of the ERU for an appropriate reason g.

Table 3

The structure of calls to Kharkiv ERUs

Causes of calls to the ERUs	Proportion of calls from their total number (γ_g)
elimination of fires and explosions	0.73
carrying out rescue operations for road accidents	0.01
assistance to the population	0.17
Patrol	0.05
Demercurization	0.03
Other	0.01

The procedure of calculations assumes that the number of EVs is first calculated for the whole settlement or for its separate administrative territory. After that, the vehicles are divided between the departments, taking into account the intensity of the flow of calls that come to them.

From the analysis of the statistical data it was found that different quantities of EVs are involved in different groups

of calls. In order to take this feature into account, the indicator of the specific number of vehicles per call (k_d) is calculated by the following formula:

$$k_d = \frac{N_{EVs,g}}{y_z}, \text{ vehicles per call,} \tag{4}$$

where $N_{EVs,g}$ is the total number of EVs in a settlement covered by the service of a particular group of calls.

In [6], the three previously identified distinct groups of challenges are liquidation of fires and explosions; elimination of emissions of dangerous chemical and radioactive substances; and assistance to the population and communal services of the settlement. From the analysis of the statistics and using calculation formula (4), the numerical values of k_d were determined as follows:

- for the first group of calls, the value of the factor is 1.41 EVs/call;
- for the second group of calls, it is 1.02 EVs/call;
- for the third group of calls, it is 1.16 EVs/call.

The types of EVs to be provided for ERUs are determined using the expert evaluation method, which is a prerequisite for taking into account the regional characteristics of the locality concerned.

The flow of calls to an ERU can be described by the Poisson distribution law [14]. Accordingly, it is possible to use mathematical models based on the Poisson distribution law to determine the likelihood of employment of a certain number of EVs in servicing a call. The above probabilistic numerical estimation can be performed using the following mathematical model:

$$P_t(w) = (\lambda \cdot t_{av})^w \cdot e^{-\lambda t_{av}} / w!, \tag{5}$$

where $P_t(w)$ is the probability of w calls occurring at time t ; w is the number of possible simultaneous calls (1, 2, 3, ...); e is a mathematical constant (an Euler number); λ is the frequency of calls to ERUs, calls/hr; t_{av} is the average time for servicing one call, calculated in hours.

Mathematical model (5) actually expresses the Poisson distribution law for the probability of large-scale rather than frequent events, and it helps establish the probability of simultaneous occurrence of a certain number of calls w . The concept of "simultaneous occurrence" must be understood as a situation where a new call is received by an ERU when the service of the previous call or calls is not yet completed. In order to take such situations into account, t_{av} is added to mathematical model (5).

In mathematical model (5), the factor λ is determined by dividing the previously calculated factor y_z by the number of hours in the calendar year. The factor t_{av} is calculated according to the statistics separately for each group of calls and departments of the ERUs in Kharkiv. The mentioned indicator is the following: for the first group of calls, 0.93 hr; for the second group of calls, 1 hr; and for the third group of calls, 0.79 hr.

Mathematical model (5) makes it possible to estimate the probability of occurrence of a certain number of simultaneous calls in a respective locality. If the factor λ is multiplied

by the factor k_d , it produces an indicator of the frequency of involvement of ERU vehicles to service the calls ($\lambda_{EVs.im}$):

$$\lambda_{EVs.m} = \lambda \cdot k_d, \text{ vehicles/hour.} \quad (6)$$

Substituting the element $\lambda_{EVs.im}$ in mathematical model (5) instead of the element λ produces a mathematical model that helps determine the probability of involving a certain number of EVs to service calls in a settlement:

$$P_t(r) = (\lambda_{EVs.im} \cdot t_{av})^r \cdot e^{-\lambda_{EVs.im} t_{av}} / r!, \quad (7)$$

where r is the number of EVs simultaneously involved in response to a call (1, 2, 3, ...).

It is necessary to calculate the probabilities of involving a certain number of EVs from the ERUs to service calls in the settlement until the following condition is fulfilled:

$$P_0 + P_1 + \dots + P_n = 1, \quad (8)$$

where $P_0, P_1, P_2, \dots, P_n$ means the probability that the call servicing is handled by 0, 1, 2, ... n EVs.

Along with the above condition, a restriction should be introduced as to the minimum number of EVs to be concentrated in an ERU. Given that more calls to a unit are related to firefighting operations, this limitation is as follows:

$$N_{ERU,z}^A \geq 1, \quad (9)$$

where $N_{ERU,z}^A$ is the number of vehicles with the main purpose of fire fighting in the z -th department of the ERU.

The introduction of this restriction also prevents a possible situation where, according to the results of the calculations, the number of EVs will be less than the number at the ERU. However, not every department will have a special vehicle, which will cause a deviation from the average time of arrival of rescue forces and means to the place of a call. To account for this limitation, a c factor was introduced into the final calculation formulae to determine the number of EVs, which is numerically equal to the number of ERUs in the settlement. This need can also be explained by the fact that in practice large-scale hazards and emergencies involve more than half of the EVs that are in the inventory set of the ERUs. Accordingly, there is a danger that no special vehicle will be left in some areas of the city.

The total number of vehicles the main purpose of which is firefighting can be determined by using the following calculation formula:

$$N_{ERU}^A = r_A + c, \quad (10)$$

where r_A is the maximum possible number of EVs that is probably simultaneously involved for the main purpose of fighting fire in response to a call.

The r_A is determined using mathematical model (7) and is numerically equal to the number of EVs the main purpose of which is firefighting when $P_t(r)=0$.

The total number of EVs for purposes other than firefighting ($N_{ERU}^{EVs.oth}$) is determined using calculation formula (11):

$$N_{ERU}^{EVs.oth} = r_{EVs.oth} + \lceil \gamma_g \cdot c \rceil, \quad (11)$$

where $r_{EVs.oth}$ is the maximum possible number of EVs that is probably simultaneously involved for a purpose other than fighting fire in response to a call; γ_g is the proportion of calls to

a respective group from their total number of those calls that are received by the ERU(s) of a settlement; c is a factor that is numerically equal to the number of the ERUs in the settlement.

In order to obtain $N_{ERU}^{EVs.oth}$ as an integer number, the result of multiplying γ_g by c is approximated, respectively, to a larger integer.

After determining the total number of EVs for respective types, it is necessary to distribute them between all the ERU departments, taking into account the intensity and structure of the flow of calls that come to them.

This redistribution can be performed by using the following objective function:

$$f(\Phi) = \frac{\sum (U_{ik} - \bar{\Phi})^2}{a-1} \rightarrow \min, \quad (12)$$

$$\Phi = \{U_{ik}\}, \quad (13)$$

where U_{ik} is a factor that is numerically equal to the ratio of the number of calls coming to the z -th department of an ERU to the number of EVs that are actually registered during the analysed period at the department; $\bar{\Phi}$ is an arithmetic mean of the sample; a is the sample volume.

The numerical values obtained using function (12) will not be integers. To obtain integer values, the fractional part of the numbers must be taken into account. Accordingly, first of all, it is necessary to round up those values that have a large fractional part, and to this end, to distribute the different types of EVs between the ERUs.

Objective function (12) was chosen in order to redistribute a certain number of EVs intended to serve the first group of calls. This was done using a Microsoft Excel 2007 spreadsheet and its Solution Search feature. Initially, the table provided the input data, namely the names of the departments of the ERU, the number of calls of a respective group per year, and the proposed number of EVs. The number of EVs in the cell "proposed number of EVs" was entered arbitrarily, but the total number of EVs corresponded to the total number of the available EVs, which was calculated using formula (10). The next value to be found was U_{ik} . After entering the value of objective function (12) into one of the cells in the table, the variance value was calculated from the numerical values of the U_{ik} factor. Then, using the Solution Finder function, the cell with the objective function entered was selected, the constraints were entered, and the value of the objective function was selected as min. Taking into account the results of the calculations, the table introduced new values of the number of EVs for the departments, and the value of the variance was calculated again and was next compared with the original to check the effect obtained. Function (12) thus allows the distribution of EVs between the departments so that the U_{ik} value for each individual department is as close as possible to its average value. Accordingly, it is possible to achieve a uniform distribution of the number of on-site visits for each individual EV in the inventory set of the ERU(s) of a settlement.

6. Discussion of the results of developing the method of completing departments of emergency rescue units with emergency vehicles

After analysing the data in Table 1, we can conclude that the number of calls to ERUs is most influenced by two factors – population and total housing stock.

Most of the calls to ERUs are caused by fires (67–78 % of the total number of calls in Kharkiv). A significant number of fires occur in residential houses and structures, as well as in open areas within a settlement. Fires in open areas are characterized by burning grass and debris and in most cases they are intentional arson. In addition, ERUs are often involved in providing assistance to the public (11–24 % of the total number of calls), as well as demercuration in residential buildings (2–4 % of the total number of calls). The fact that units are most often involved in operational activities in housing facilities and open areas near them explains the impact of the first and second factors on the number of calls.

Accordingly, in the process of determining the likely number of calls to ERUs, the total area of housing stock that is concentrated in the relevant administrative territory of the city can be used as the main factor. The advantages of this factor compared to the population of the administrative territory are the following:

- the total area of the housing stock is constantly kept a record of in settlements, and the official census was last conducted in 2001;
- population is a rather variable factor, which depends on migration, childbirth and mortality, seasonality and other factors, and the factor of the total area of the housing stock is relatively more stable.

Taking into account the identified features, the total area of housing stock was chosen as the main factor for the development of a predictive model for determining the number of calls to ERUs for work on hazards and emergencies in a settlement. In this case, the identified problem was that each administrative district of a city is divided into zones of responsibility of the ERUs, and the accounting of the total area of the housing stock is conducted in general by separate administrative-territorial districts. The solution to this problem required determining the part of the calls that referred to each department of an ERU whose service area is within one or another administrative territory of the city. Those values were further used to determine the estimated number of calls to each individual department of the ERU, taking into account the total number of calls that would occur in the respective administrative territory. Before that, we first determined the average number of calls to each department of the ERU per year and estimated its standard deviation. Overall, the period under analysis was from 2010 to 2018.

The next stage was to build the predictive model to determine the likely number of calls to ERUs, depending on the total area of the housing stock that is concentrated in the administrative areas of the city. Determining the estimated number of calls that can be received individually by each department of an ERU required taking into account β_z , for which the corresponding calculation formula (3) was proposed.

In the final form, the proposed method of completing ERUs with EVs entails performing four successive stages, which are shown in Fig. 2.

Fig. 2 shows that the stages of the calculations primarily involve the development of a predictive model and the use of it to determine the number of calls to ERUs to eliminate hazards and emergencies. The determined factor of the number of calls to ERUs is further used to calculate the necessary number of EVs for completing the departments.

The condition of the proposed method is that the call flow must be Poisson.

In order to ensure greater accuracy of the results, the database of the Emergency Dispatch Service of the Emergency Coordination Centre, which are mainly located at the Departments and Head Offices of the SES of Ukraine in the respective areas, can be used.

The method of completing ERUs with EVs proposed in this study was implemented in the case of the city of Kharkiv.

The results of calculating the total number of EVs for the ERUs produced the following values:

- the number of EVs for servicing the first group of calls is 29 vehicles;
- the number of EVs for servicing the second group of calls is 5 vehicles;
- the number of EVs for servicing the third group of calls is 10 vehicles.

The results of implementing the distribution of a certain number of EVs between the departments of the ERUs are given in Table 4. The main departments of the ERUs in the city of Kharkiv are the State Fire-Rescue Departments (SFRDs), so the allocation was performed for them.

After determining the total number of EVs and their redistribution between the ERUs, we studied the probable effect of the decisions made. Performance was determined by the average time for the department EVs to arrive at the call point, and it was used to assess the level of operational readiness of the ERUs for the intended purpose.

To this end, the average speed of the EVs in the city of Kharkiv was first determined by conducting a sample survey. In order to obtain adequate research results, it was necessary to determine the sample size (E) of the total data set. For this purpose, we used the following calculation formula:

$$E = \frac{1}{\Delta^2 + \frac{1}{D}}, \tag{14}$$

where Δ^2 is the error of representativeness; D is the total number.

With 0.05 as the chosen value of the error of representativeness, which is acceptable for technical calculations, and the total number of 6,754, the obtained sample size was 378.

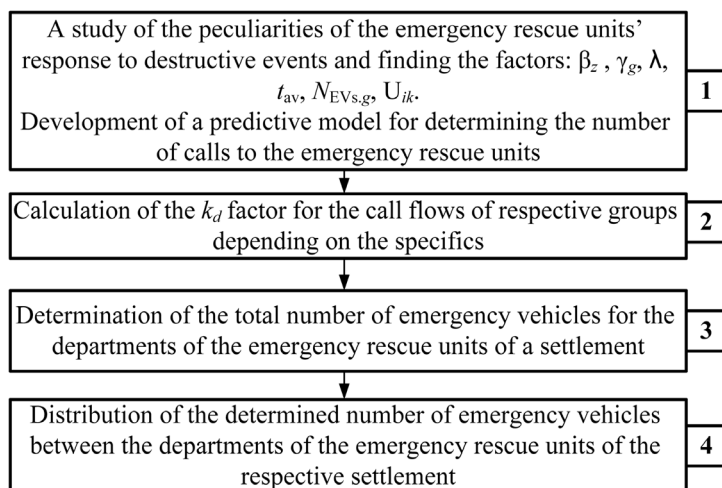


Fig. 2. Stages of calculations using the method of determining the number of emergency vehicles for emergency rescue units

Table 4

The proposed number of different types of EVs for the ERUs of Kharkiv

The proposed number of EVs	The name of the department																		
	SFRD-1	SFRD-2	SFRD-3	SFRD-4	SFRD-5	SFRD-6	SFRD-7	SFRD-8	SFRD-9	SFRD-11	SFRD-17	SFRD-18	SFRD-22	SFRD-25	SFRD-26	SFRD-27	SFRD-32	SFRD-36	SFRD-41
for servicing the first group of calls	2	2	1	1	3	1	1	2	2	2	2	3	1	1	1	1	1	1	1
for servicing the second group of calls	-	1	1	-	-	-	-	1	1	-	-	1	-	-	-	-	-	-	-
for servicing the third group of calls	1	1	1	-	-	1	-	1	1	1	1	1	-	-	-	-	1	-	-

In order to randomize the sample of 378 from 6,754, the ‘Select’ function of the Microsoft Excel 2007 spreadsheet processor was used, which allowed for repeated random sampling.

After that, the ERU locations and places of occurrence of hazards and emergencies on the territory of Kharkiv were put on the map. Further, the Scribble Maps mapping service was used to determine the distance between the previously specified locations along the road network. As a result, the average speed of the EV traffic along the road network of the city of Kharkiv was found to be 18.9 km/hr.

The next step was to determine the average time for the units to arrive at the location to service the first group of calls. For this purpose, only the data that were relevant to the first group of calls were first selected from the general data set. The sample size was then calculated and the data were selected in the previously described way. After that, the distance between an ERU location and the place of a call was determined. Taking into account the determined average speed of the traffic flow on the road network of the city of Kharkiv, the average time of arrival was found. Similar calculations were made for the other groups of calls. The above procedure of calculations was carried out for two cases, namely with the existing variant of completing ERUs with EVs and the proposed, using the developed method.

According to the research statistics, it has been established that the average time of arrival of EVs at the places of calls under the existing variant of completing ERUs with EVs is as follows:

- at the location of servicing the first group of calls – 9 minutes;
- at the location of servicing the second group of calls – 29 minutes;
- at the location of servicing the third group of calls – 11.2 minutes.

Provided that the ERUs are completed with EVs in accordance with the variant proposed using the developed method, the estimated time of arrival of EVs at the places of calls is as follows:

- at the location of servicing the first group of calls – 9 minutes;
- at the location of servicing the second group of calls – 11.46 minutes;
- at the location of servicing the third group of calls – 9.24 minutes.

By comparing the mean arrival time values, the following results were obtained:

- a) the average time of the EV arrival at the location of servicing the first group of calls remained unchanged, which is a consequence of the previously accepted restriction (9);

b) the average time of the EV arrival at the location of servicing the second group of calls, on condition of implementing the proposed variant of completing the ERUs, can be reduced by almost 60.5 %;

c) the average time of the EV arrival at the location of servicing the third group of calls, on condition of implementing the proposed variant of completing the ERUs, can be reduced by almost 17.5 %.

The average time of arrival can be reduced by completing ERUs with certain types of EVs and redistributing these vehicles between the departments, taking into account the operational situation in a settlement.

In the process of determining the number of EVs in this study, the main condition to be taken into account was that their number at an ERU should be sufficient to provide service for several calls at a time. Besides, the EVs’ location was determined taking into account the condition of ensuring uniform loading of units with operational activities. As stated earlier, the average time of the units’ arrival at the location of servicing the first group of calls remained unchanged and did not exceed 10 minutes. Thus, this value corresponds to the normative index in developed countries of the world. According to the results of the evaluation, the proposed variant of completing ERUs ensured that the average time of the units’ arrival at the location of servicing the third group of calls was also less than 10 minutes. The time of the units’ arrival to service the second group of calls, even after completing the ERUs with EVs according to the proposed variant, was more than 10 minutes. It is possible to achieve a greater reduction in arrival time by equipping individual departments of an ERU with a certain type of EVs, which in turn allows expanding the list of the tasks performed by these departments. However, it is noteworthy that an increase in the number of EVs increases the material costs associated with their acquisition and subsequent maintenance.

In the future, it is planned to develop a method for estimating the response time of ERUs depending on the peculiarities of completing them with EVs.

7. Conclusion

1. It has been established that the flow of calls coming to the departments of emergency rescue units has a certain structure from which it is possible to distinguish several distinct call flows depending on the specifics. The first is the call flow associated with fires and explosions. The second is the call flow associated with spills and/or emissions of harmful chemicals and radioactive substances. The third is the flow of calls that is related to providing assistance to the population and communal services of a settlement. The operational activities in response to these call flows involve different quantities of emergency vehicles, which was proposed to be estimated by k_d in this study. It has been determined that the number of calls to the departments of emergency rescue units depends on the total area of the housing stock of the respective administrative territory of a city. This dependence was approximated by a polynomial trendline, for which a regression equation was composed. This equation helps determine the probable number of

calls to the departments of the emergency rescue units of a settlement to eliminate hazards and emergencies, taking into account changes in the total area of the housing stock.

2. A method is proposed to complete the departments of emergency rescue units with emergency vehicles, taking into

account the operational situation in the areas of their on-site visits. The results of the research show that the implementation of this method in practice can reduce the time of the units' arrival at the place of servicing the second group of calls by almost 60.5 % and the third group of calls by almost 17.5 %.

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