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Svitlana DANSHYNA, Artem NECHAUSOV

National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine

METHOD OF INFORMATION TECHNOLOGY FOR STRUCTURE ANALYSIS OF URBAN NETWORK FIRE-RESCUE UNITS

The subject *of this study is the process of analyzing the structure of the network of fire-rescue units of the city in the context of optimizing their spatial distribution.* ***The purpose*** *of this work is to increase the objectivity of decisions made while forming a city network of fire-rescue units by creating an information technology (IT) method for analysis of its structure based on the use of spatially distributed data.* ***Objectives****: to find ways to improve the level of fire safety, analyze existing approaches to the formation of a network of fire-rescue units, considering the peculiarities of building and organizing a network, and adapt the classical problem of placement; to propose a method for solving it to minimize the distance between the fire-rescue unit and the possible place of fire while ensuring maximum coverage of the territory by fire service; and to develop IT structure for its implementation based on the information flow model of the process of analyzing the fire-rescue units network using a geospatial approach. The following* ***results*** *were obtained. The study of the classical location problem and its adaptation to real problems arising from the analysis of the urban network of fire-rescue units made it possible to represent it as a set of independent complete bipartite graphs. To search the location of network nodes while solving an adapted problem, an IT method is developed, which, based on the p-median model, combines the author's methodology for studying information processes and methods of geospatial analysis. Summarizing the requirements of the current legislation, a set of input and output IT data and a set of operations have been formed. The representation of the IT structure in the form of a data flow diagram explains how the set of factors is processed and generalized when making decisions on the creation and / or improvement of the existing city fire department.* ***Conclusions.*** *The results of the bibliographic search confirm the need to consider the spatial features of the area where it is planned to create a fire-rescue unit, as well as the spatial configuration of the urban network of existing fire stations, to evaluate its effectiveness using an integrated indicator. This requires the development of specialized methods focused on the use of geo-information systems for their implementation in decision support systems. Scientific and methodological support for IT has been developed, which gives local authorities a tool for analyzing fire safety in the city to create and / or improve the existing fire protection. An experiment to study the capabilities of the proposed method based on volunteered geographic information on Kharkiv city showed the effectiveness of its use for solving classical problems of placement, considering the accepted restrictions on the spatial availability of fire-rescue units. At the same time, additional opportunities appear in the formation of options for improving the network of fire-rescue units, considering their spatial distribution, workload, accessibility, and the resulting areas of coverage / non-coverage by the fire service. For example, the fire service coverage area of the existing structure of fire stations has been assessed. During the regulated time, it reaches 70% of the Kharkiv city area, and depending on the real road traffic, it can vary from 64.61% to 73.44%. It is illustrated that the creation of two additional fire and rescue units in the northern and southern parts of Kharkiv will increase the coverage area by approximately 5%, on average increasing it to 75.1%.*

Keywords: *p-median model; geospatial analysis; model of information flows of the process; IDEF0-model; data flow diagram; fire service coverage area.*

Introduction

Since 1995, the International Association of Fire and Rescue Services (https://www.ctif.org/) annually summarizes statistical data on fires in 27–63 countries worldwide, where 0.9 – 3.8 billion people live. In the surveyed countries, 2.5 – 4.5 million fires were recorded annually, in which 17 – 62 thousand people died. At the same time, a significant risk of being caught in a fire is recorded in Cyprus, where on average; there were 8.0 fires for every 1000 people. A significant risk of dying in a fire is observed in the Republic of Belarus, where an average of 8.5 people dies in every 100 fires [1]. Note that in Ukraine from 2020 to 2022, on average, for every 1000 people 2 fires are recorded, and on average 2 people die in 100 fires, which, compared to anti-leader countries, characterizes optimistically the state of the country's fire safety. However, in terms of regions of Ukraine, the analysis of analytical data from the Institute of Public Administration and Research in Civil Protection (https://idundcz.dsns.gov.ua/statistika-pozhezh/) shows the following results (Fig. 1). In 15 regions of

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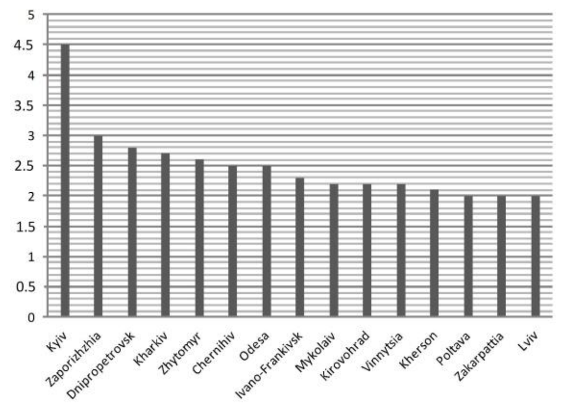
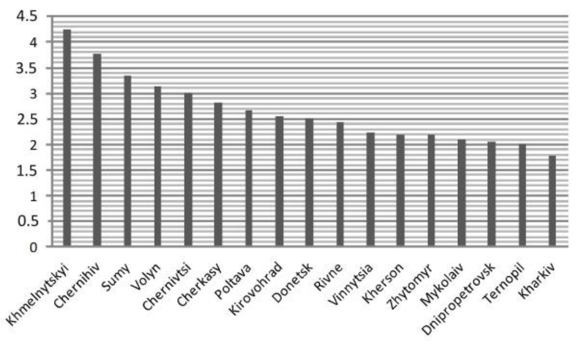
Ukraine, the country's average risk of being caught in a fire was exceeded (Fig. 1, a). For example, in the Kyiv region, its average value for three years (from 2020 to 2022) is 4.5 (i.e., there are 4.5 fires for every 1000 people), while in 2020 its value reached 5.0 and in 2022 it reached 4.7. In 16 regions of Ukraine, the country's average risk of death in a fire was exceeded (Fig. 1, b). For example, in the Khmelnytskyi region, its average value for three years is 4.25 (that is, more than 4 people die on average in 100 fires), while in 2021 its value reached 4.65.



a



b

Fig. 1. The indicators of integral territorial fire risks for Ukraine (in some regions): a – the risk of being caught in a fire; б – the risk of dying in a fire

The above statistics emphasize the need for a systematic increase in the level of fire safety in the country through the development and implementation of measures for the timely response to fires, the elimination of their consequences, and the prevention and prevention of emergencies associated with fire.

State of the Art

The reform of local governments gave the authorities significant powers to make decisions independently in the field of civil protection. First, this concerns the issues of ensuring fire safety, progress in solving which is associated with the formation and organization of fire-rescue units [2]. The success of the functioning of the local fire department, the timeliness of response to calls, and its rescue capabilities directly depend on the availability of the required number of fire-rescue units, their reasonable location, the availability of the required type and number of fire and rescue vehicles, and the number of personnel. [2, 3]. Determining how many and where to place fire-rescue units in a given area is the most important issue that local governments face [2]. The optimal solution is the one that minimizes the total losses from a fire and the cost of the provided measures, which is an economic compromise between the cost of damage and the total costs of organizing and operating fire stations. However, such a simplified interpretation of the placement problem is contradictory and does not achieve all the goals of ensuring fire safety [4]. However, fire rescue capabilities can be effectively improved by the scientific layout of fire stations and forming the respective network [5].

The results of the bibliographic search (https://www.sciencedirect.com) confirm the existence of two main approaches to the formation of the structure of the network of fire-rescue units in the planning area: one is based on a statistical assessment of the probability of ignition and fire hazardous zones [6 – 9], and the other is based on the analysis of the existing structure of settlement and development [5, 10].

Over the years, cities have become much larger and more functionally diverse, and their population is constantly increasing. Large volumes, complex functionality, and a high density of crowds characterize modern urban buildings. During urban expansion, these buildings may intersect with elements of industrial zones (for example, factories, warehouses, etc.), border on buildings of old and / or homestead buildings, may closely adjoin each other, occupy fire-prevention passages, etc. At the same time, motor roads become more winding and narrow, and it is increasingly difficult for fire engines to get to the place of fire along them [6 – 8]. Therefore, old fire protection planning cannot meet the demand of new cities, which has brought difficulties to the layout design of urban fire protection.

The analytical hierarchy process is a common evaluation method for fire hazardous zones in the layout design of urban fire protection. The process of analytical hierarchy is a common method in the area evaluation of fire zones. It allows you to assess which of the fire risks is dominant, focus on its leveling, develop fire prevention measures with a view to improving resource allocation strategies and urban renewal, including the redevelopment of old, worn-out, or low-populated urban areas, and build an appropriate structure of fire services [6, 7]. The fuzzy comprehensive evaluation method is also a common method of determining fire probabilities and fire zones and is used in the design of fire protection. The main advantage of this method is that the qualitative data can be quantified, which makes the results more intuitive and comparable [6, 8]. However, in conditions where many fire risk assessments are qualitative and difficult to quantify [9], an integrated approach is needed to solve the problem of choosing a location for fire stations.

The second approach is the most common (for example, its main idea is implemented in Ukrainian Building Code B.2.2-12:2019 [10]). Very often, the location of fire-rescue units and their equipment is determined depending on the population of the city, considering the area of departure, based on the length of the route [10, 11]. Therefore, as a criterion for optimal placement, consider the time required for the fire service to respond to a message about a fire and arrive at the place of its occurrence [12 – 14]. This response time is not only dependent on resources allocated to fire stations but also on the spatial configuration of demand (i.e. number of fires) and supply networks (i.e. relative spacing of fire stations and network structure). Response time is a major concern for all public emergency service agencies [5, 13]. There is a correlation between the risk of life loss and the response time to attend calls for fire emergencies. According to estimates, Ukraine's fire fatality rate is 2 people per 100 fires [1]; therefore, devising further initiatives to proactively diminish the potential fire-related tangible and intangible damages seems necessary [2].

Problems with existing systems

First, the complicated layout of urban geography has laid many hidden fire hazards for the city and has put forward higher requirements for the layout of urban fire protection planning based on fire risk [6, 8, 9]. Statistical fixation of fire hazardous zones [9] together with estimates of fire probabilities [5, 6, 8] are most often used in the development of measures to prevent fires, when choosing a place for a new fire-rescue unit in the structure of an existing network. These data can be considered as one of the inputs for finding the Pareto-optimal solution to achieve the maximum coverage of the planning area with a certain (minimum) number of fire trucks [5, 6].

Second, with rising urban populations and city expansions, the demand for more fire services consequently increases. It becomes critical to plan the location of emergency facilities effectively to adequately service the population and ensure the protection of lives and infrastructure [11]. However, as noted in the studies [2, 15, 16], the solution to the problem of placement is significantly complicated by the need to consider the road infrastructure, traffic intensity on the roads, possible traffic jams, obstacles (railway crossings, water obstacles, the presence of road sections on which fire rescue equipment is not will be able to move through the overall dimensions or technical characteristics), etc. As a result, the effectiveness of the local fire department depends on the level of coverage of the exit area, considering travel time, road infrastructure, and other realities that firefighters face when responding to an emergency [17 – 19].

The combination of these factors focuses on the geographical nature of the task and requires taking into account the spatial features of the area where it is planned to organize a fire-rescue unit, as well as the spatial configuration of the entire city network of available fire stations, the effectiveness of which is determined by several factors, including time, distance, settlement structure, and building density [20–22]. In this case, spatial optimization methods and geographic information systems (GIS) have become promising, as they are successfully used in modeling the location of public facilities and provide new opportunities to increase the objectivity of decisions on the number of fire stations and the choice of their location in a particular area [8, 23, 24].

Objectives and novelty

Thus, the **aim** of this work is to increase the objectivity of the decisions made when forming an urban network of fire rescue units. The **novelty** of this study is the creation of an information technology method for analyzing the structure of an urban network of fire rescue units based on the use of spatially distributed data, combining statistical estimates of the probability of ignition and considering the existing structure of settlement and city development to find ways to improve the level of city fire safety. The **subject** of this study is the process of analyzing the structure of the network of fire-rescue units of the city in the context of optimizing their spatial distribution.

1. Materials and methods of research

A network of fire-rescue units is a set of fire-rescue units in the planning area, the number of which is sufficient to ensure fire safety, guaranteeing the necessary response to a fire emergency call and arrival for liquidation at the place of its occurrence within a specified time. Based on the proposed definition, the network structure is determined by the necessary and sufficient number of fire-rescue units (M) and their spatial distribution [2].

In accordance with the requirements of State Standard-8767, the approximate number of fire-rescue units depends on the number of basic fire and rescue equipment, which is estimated depending on the popula-

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tion in the planning area. For example, in the general case, for a settlement with a population of less than 1 thousand people, at least one fire truck is needed, which means that one fire-rescue unit is organized [10]. The estimated number of units thus obtained is finally corrected in their spatial arrangement, considering the time of arrival at the call site.

1.1. Problem statement

Let us assume that there is sufficient equipment to extinguish all fires that have simultaneously occurred in the planning area. In this case, the main task is to increase the spatial accessibility of the population to the fire service, which guarantees timely response to emergencies, minimizes property losses, and reduces the number of injuries and deaths [18]. At the same time, from the condition of efficient use of resources, we assume that the service areas of individual fire-rescue units do not intersect (or their intersection is minimized) [4].

Based on the “center-periphery” model proposed by J. Von Thunen [25], we consider the fire-rescue unit as a “center” designed to respond to a fire (in terms of the “center-periphery” model – to “satisfy demand”). In this case, the network of fire-rescue units is the union of the M-th number of complete bipartite graphs of type $K_{1,D_{I+1}}$, each of which has negligibly little effect on the other graphs of the network. In turn, the spatial structure of a single graph $K_{1,D_{I+1}}$ formed by the set of vertices $U=\{u_j \mid j=\overline{1,(i+1)}\}$ (while $i=1,\ldots,I$) with coordinates (x_j, y_j) and a set of edges (no loops) $E=\{e_k \mid k=\overline{1,i}\}$. Each edge of the graph e_k corresponds to its length $l_k>0$ (для $e_k=(u_1,u_j)$ while $j=\overline{2,(i+1)}$ designation introduced $l_{1,j}=l_k$). Thus, for any pair of vertices (1,j) ($j\neq 1$) the spatial accessibility function as a function of distance (length) $L((x_1,y_1),(x_j,y_j))$ can be found between the vertex 1 («center») with coordinates (x_1, y_1) and an arbitrary vertex j with coordinates (x_j, y_j), and the task of placing the fire-rescue unit will take the following form [24, 25]:

$$\underset{(x_1,y_1)}{\arg\min} F(x_1,y_1)=\underset{(x_1,y_1)}{\arg\min}\sum_{j=2}^{I+1} L((x_1,y_1),(x_j,y_j)), \quad (1)$$

where $L(\cdot)$ – is a function of the distance between the fire-rescue unit and the locations where a fire might start.

Function (1) corresponds to the classical *p*-median placement model [24, 26], minimizing the longest distance or travel time between the "points of demand" and the "centre". In this case, the value of $L(\cdot)$ is regulated by Building Code B.2.2-12:2019 and the relevant orders of the State Service of Ukraine for Emergency Situations [2, 10], that is:

$$L((x_1,y_1),(x_j,y_j))\le \Lambda \quad (2)$$
$$\text{for } \forall j=\overline{2,(i+1)} \text{ while } i=\overline{1,I}.$$

The value Λ is selected from the condition of providing the necessary response time to a fire message. With an average speed of fire and rescue equipment (25 ... 45 km/h) for cities and urban-type settlements, its value is 10 min, and for rural areas, it is 20 min. Thus, inequality (2) limits the real distance between the fire-rescue unit and the places where a fire may start, directly affecting the coordinates (x_1, y_1).

1.2. Fire-rescue units location selection

Finding the location of the “center” and performing an analytical search for its coordinates is possible with multicriteria optimization of function (1) [26 – 28]. On the one hand, by solving a system of differential equations of the form:

$$\begin{cases} \dfrac{\partial F((x_1,y_1))}{\partial x_1}=0; \\ \dfrac{\partial F((x_1,y_1))}{\partial y_1}=0 \end{cases}$$

the goal of minimizing the maximum distance between the fire-rescue unit and the possible place of fire is achieved [26, 27]. On the other hand, the introduction of constraint (2) makes it possible to exclude the situation when only microdistricts adjacent to fire-rescue units are covered by the fire service [28]. At the same time, considering the network structure of fire-rescue units in the planning area, finding the location of the “centers” of p-median models – network nodes – allows covering the maximum number of “demand points” by each “center” [26]. When evaluating efficiency as an integrated indicator, we can consider the area of coverage of the planning territory by fire service. The necessity of achieving the goals of optimization of function (1) in the presence of constraints (2) leads to certain computational difficulties and requires the development of scientific and methodological support for finding the M-th number of coordinates ( ), for example, based on geospatial analysis.

The search for a solution to the generated placement problem (1) under constraint (2) is carried out as part of the information process of analyzing the structure of the fire-rescue units network. Based on the requirements of regulatory documents [2, 10], we systematize the information flows of this process and, using the author's research methodology [29, 10], we conceptually represent it in the form of a set-theoretic model of information flows:

$$I\_Pr = (V, O, A, \psi, Z, \varphi)\,, \qquad (3)$$

where V – a set of process inputs;

O – a set of process outputs;

Z – a set of documents regulating the process;

A – set of operations that implement the process.

Internal contents of sets V, O and Z models (3) are disclosed in Fig. 2. In Fig. 2, in accordance with the IDEF0 methodology, the symbolic model (3) for clarity and ease of perception of information flows while maintaining the rigor and formality of the presentation is shown in the form of a context diagram [30, 31]. Here, as a means of implementing set operations, a GIS is proposed that allows a person responsible for fire safety to plan appropriate activities based on a spatial analysis of data on a settlement [23, 32].

In model (3), the set $V = \{v_1, v_2, v_3, v_4\}$ is converted to set $O = \{o_1, o_2, o_3, o_4, o_5\}$ by stepwise implementation of set operations $A = \{a_1, a_2, a_3\}$ in that order [2, 15]:

Stage 1. Evaluate the existing network structure of fire-rescue units.

Stage 2. Evaluate the scope of the fire service.

Stage 3. Select options for improving the network of fire-rescue units.

This set transformation is defined by the function of outputs ψ – displaying the view [29, 30]:

$$\psi : A \times V \rightarrow O\,, \qquad (4)$$

which for a given time determines the output of the process O(t) depending on the set of input data V(t) and operations performed A(t).

For the network structure analysis process of fire-rescue units, considering the rules formed in the work [33], let's open the internal content of the function ψ with a graph (Fig. 3), in which vertices correspond to operations from the set $A = \{a_n\}, n = 1,\ldots,3$, edges – to possible transitions from operation to operation.

On Fig. 3 the weight of each edge is an indication of an element of the set $V = \{v_m\}, m = 1,\ldots,4$, which defines the transition from performing a single operation a_n to another, as well as to an element of the set $O = \{o_q\}, q = 1,\ldots,5$ as a result a_n, necessary to perform subsequent operations of the process. For example, at the initial time t, the input of the operation a_1 of the elements v_1 and v_2 allows to form outputs o_1 and o_2, which are necessary for further operations a_2 and a_3. Further, as the results of the operation a_2 outputs o_3 and o_4 are being formed by generalization of the input v_3 and output o_1; at the same time o_4 enters the operation input a_3 etc.

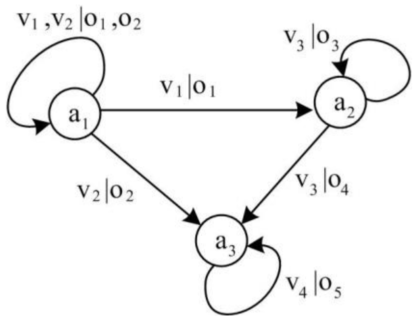

Fig. 3. Graph representation of a function (4)

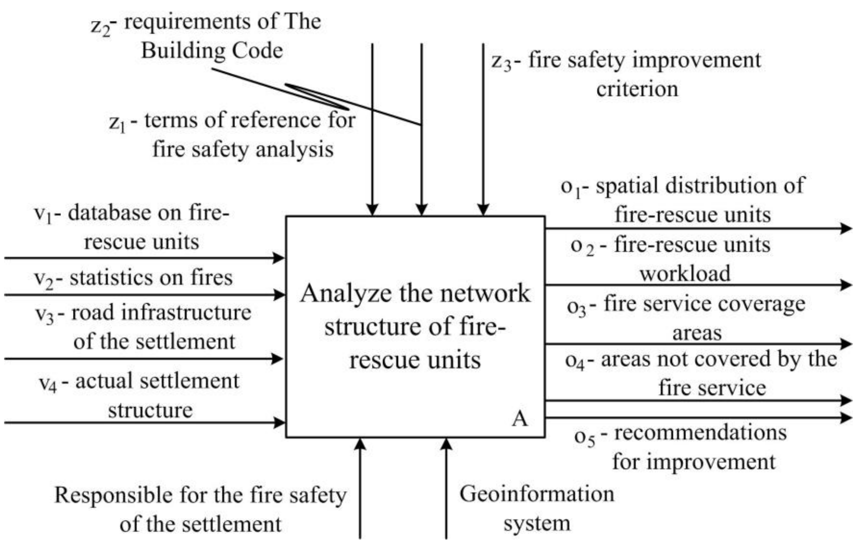

Fig. 2. Context diagram of the process of analyzing the structure of the fire-rescue units network

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To normalize the internal content of the information flows of model (3) when converting input data into output data, a set of regulatory documents is required. They are defined by a set $Z = \{z_1, z_2, z_3\}$, and the normalization rules are set by the update function φ [29, 30]

$$\varphi : V \times Z \rightarrow V. \quad (5)$$

In accordance with mapping (5) at time t, the input of the process V(t) depends on the input at the previous time i of the set of regulatory documents Z(t). For each element of the set V, the function φ defines the implementation $v_m = \varphi(v_m, z_r)$, where $\forall v_m \in V$, $\forall z_r \in Z$ while $m = 1,...,4$; $r = 1,...,3$.

Thus, depending on the initial input data, the content of regulatory documents, and the accepted set of operations, when analyzing the structure of the network of fire-rescue units, the values of inputs and outputs are transformed discretely in time [29, 33]. These dynamics can be easily and clearly explained using the Data Flow Diagramming methodology.

Data Flow Diagramming is a visual modeling system that allows the output data elements of the information process to be presented due to an operation (function) for processing external and internal data flows [31, 33]. Simultaneously, the combination of formal and visualization methods in the methodology provides a convenient tool for creating a set of graphical models – Data Flow Diagram (DFD), revealing the mechanism for implementing the model (3). Based on the Yourdon notation, the diagram for the I_Pr process combines data flows and sources of their receipt (External Entity and Data Store), shows the sequence of their processing and transformation [31], taking into account the requirements of the current legislation (Fig. 4).

The developed DFD, based on the proposed scientific and methodological support, models, how in accordance with the request of local governments, a fire safety analysis is carried out in a settlement to create and/or improve the existing fire protection and reveals the structure of information technology (IT) analysis of network fire-rescue units.

Thus, the proposed method, considering the statistics on fires and their consequences for previous periods, considering the current settlement structure and the existing road infrastructure of the settlement, allows us to find a solution to problem (1) subject to constraint (2), focusing on real volumes funding coming from local budgets. The results, obtained when using the developed method when implemented in the relevant IT, will make it possible to make informed decisions on the creation and/or improvement of the local fire department, for example, in the context of reforming the State Emergency Service, when the costs of maintaining it are compensated by reducing property damage and preventing deaths due to fires during account of spatial optimization of fire-rescue units network elements.

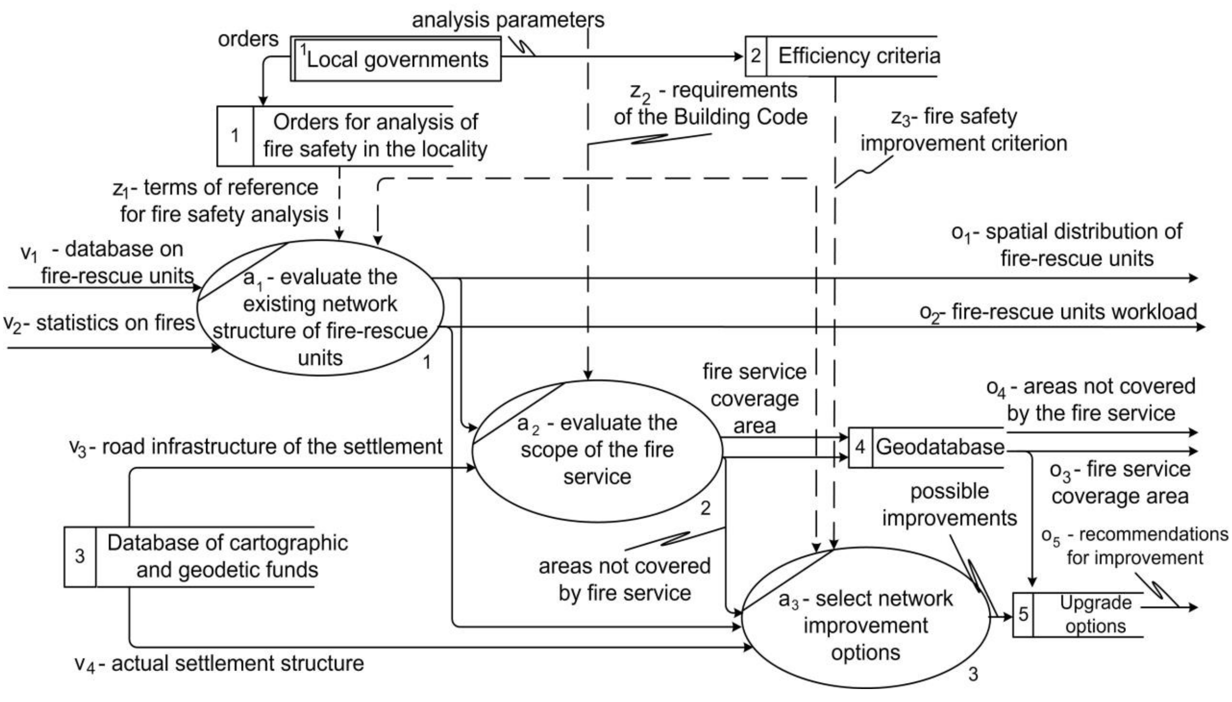

Fig. 4. Data Flow Diagram of the process as a structure of information technology for analyzing the structure of the network fire-rescue units

2. Results

Analyzing Fig. 1, a, we note that Kharkiv region is in the top five areas of anti-leaders in terms of the risk of being in a fire. According to statistics for 2022, the risk of being caught in a fire is 2.7.

At the same time, according to the Institute of Public Administration and Research in Civil Protection, for ten months of 2023, Kharkiv region took fourth place in the number of recorded fires: their number reached 4757, 2696 cases of which were registered in cities and urban-type settlements. This represents 56.7% of the total number of fires and exceeds the share of urban fires in the country by 5.0%. It should also be noted that in the first ten months of 2023 Kharkiv region exceeded by 18.5% the average statistical value for Ukraine of the number of deaths due to fires per 100 thousand population – the region is among the top ten anti-leading regions by this indicator. Of course, the distribution of the number of fires is significantly influenced by the intensity of hostilities within individual regions of Ukraine, as well as by the movement of population and industrial capacity from the eastern regions to the west of the country. However, the above statistics once again emphasize the need to improve measures to ensure fire safety in Kharkiv region and, in particular, in Kharkiv city.

To illustrate the effectiveness of the proposed ideas, let's analyze the network of Kharkiv city fire stations using the developed method. Due to the authors' lack of access to official statistics, we will rely on volunteered geographic information (VGI). VGI is spatial data that are gathered and shared by individuals to derive information about the world. This type of information is very valuable for scientists; numerous studies highlight the effectiveness of using VGI during crisis events, and have found intrinsic value for rescue teams, relief workers and coordinators, as well as the affected population [34].

Based on the VGI for the city of Kharkiv, data on eighteen operating state fire-rescue units were summarized, and an appropriate database was formed (input v_1) (Fig. 5).

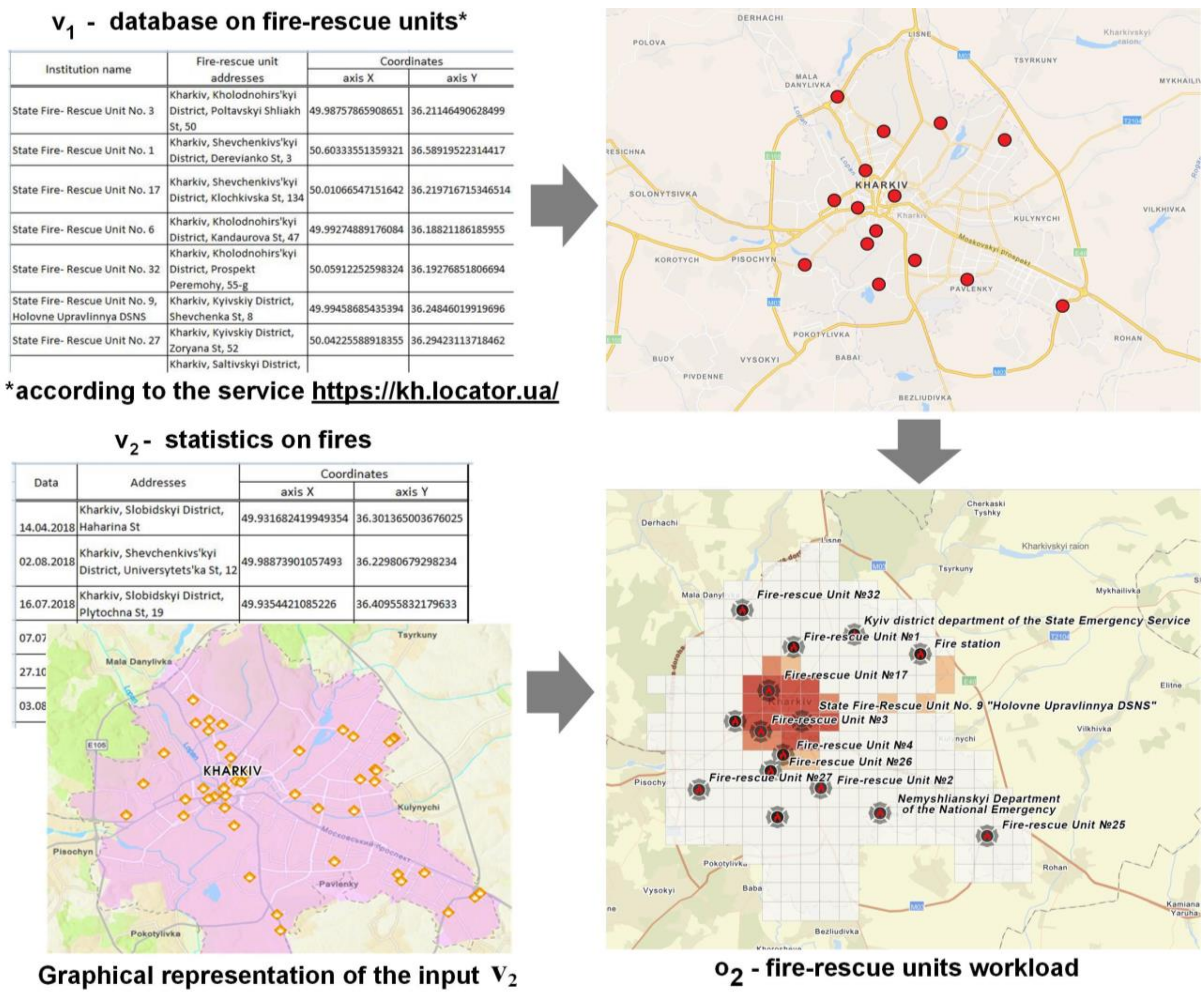

Fig. 5. Shaping outputs o_1 and o_2 on operations a_1

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Owing to the lack of publicly available generalized statistics on fires, in accordance with the VGI concept, data from social networks and information portals were analyzed to form the input v_2, for example, https://apostrophe.ua/, https://2day.kh.ua/, https://kh.vgorode.ua/, etc. Considering the recommendations of [2], the systematized information on fires in the city for the period from 2018 to the beginning of 2022 (excluding the period of military actions) (Fig. 5). Within the framework of the proposed method, ArcGIS Online and its internal road network processing module "Network Analyst" are recommended as a VGI processing tool.

Analysis of the spatial distribution of fire-rescue units (output o_1) shows that a significant part of them is concentrated in the center of Kharkov. This correlates with the conclusions of [35], where the areas of the city's historical development are prone to fire hazard, which determines the existing spatial distribution.

The workload of fire-rescue units (output o_2) was assessed by the Getis-Ord Gi statistic as a function of ArcGIS Online, which considers fire location statistics in the context of neighboring locations, identifying statistically significant "hot spots", fixing areas of potential fire danger (red areas) in the city and determining busiest fire stations (Fig. 5). Thus, three fire-rescue units turned out to be the busiest – State Fire-Rescue Unit No. 3, State Fire-Rescue Unit No. 17 and State Fire-Rescue Unit No. 9 "Holovne Upravlinnya DSNS" – fire-rescue units in the center of Kharkiv with a characteristic dense building and a large number of old buildings.

For a long-term planning perspective in the context of the further expansion of the city [17], an assessment was made of the availability of fire-rescue units and areas of coverage / non-coverage by fire service (exits o_3 and o_4). Considering the constraint (2), the coverage areas are determined based on the travel time [14] according to the actual road infrastructure of Kharkiv (input v_3) from each fire-rescue unit to nearby fire points (Fig. 6).

Thus, it was found that the existing network of fire-rescue units in Kharkiv serves an average of 243.54 km^2 of the city's territory, which, in accordance with the adopted efficiency criterion, constitutes 70% of the fire service coverage zone. At the same time, urban road traffic significantly affects the service area [16], adjusting its value depending on the day of the week and time of day (Table 1).

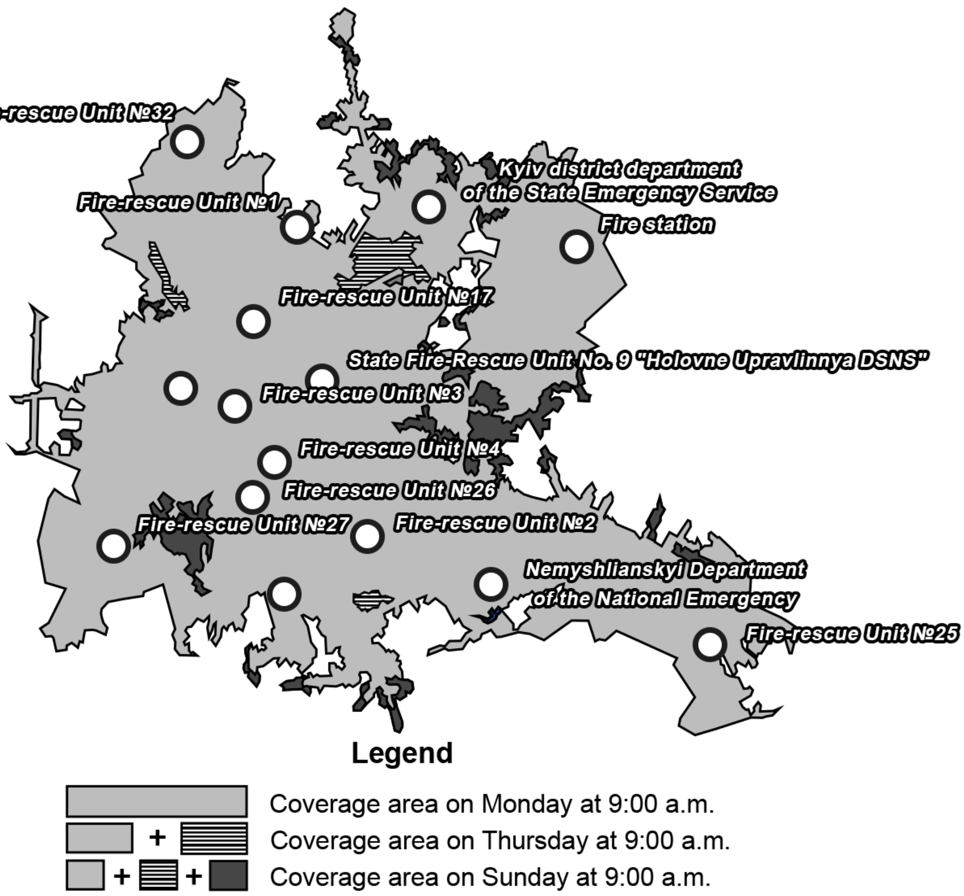

Fig. 6. Output shaping o_3 on operations a_2

Table 1
Coverage area of the fire service city's territory, considering road traffic, %

Week day	Time period		
	at 9:00 a.m.	at 4:00 p.m.	at 10:00 p.m.
Monday	67.42	67.75	72.41
Thursday	65.11	64.61	73.12
Sunday	71.10	71.30	73.44

An analysis of the functional structure of city districts not covered by the fire service showed that only some of them belong to housing development, most of them are landscape and recreational (for example, the botanical monument "Pomerki", Zhuravlevsky Hydropark, Shcherbachevsky Bor, etc.) and industrial areas (for example, Kharkov Bearing Plant, Kharkov Mechanical Plant, Shevchenko Plant, etc.) (Fig. 7). This means that when forming the output, recommendations for improving the structure of the Kharkiv fire-rescue units network will differ.

For landscape and recreational areas, where there is practically no developed road infrastructure, all security measures should be aimed not at fighting fires, but at eliminating their root causes [6].

For industrial zones, it is promising to create voluntary fire brigades [13, 36], whose members are trained on the basis of the State Emergency Service, which helps to reduce fire risks, increases the level of information about fire safety, and stimulates a positive attitude among the population. Members of volunteer fire brigades are the first to be involved in providing timely assistance directly at the enterprise. As employees, they have equipment, overalls and special knowledge for prompt response to fires. A successful example of the implementation of such an option for improving the network of fire-rescue units can be considered the creation of a voluntary fire brigade at the Kharkov Bearing Plant, which correlates with the findings of the paper [36].

An option to improve the network of fire-rescue units in the residential area is to create additional fire stations in accordance with the real structure of the city's settlement [11], considering the requirements of Building Code B.2.2-12:2019. For example, to increase the coverage area of residential microdistricts of the city, it was proposed to create two additional fire stations. It is recommended that they be located in the northern and southern parts of the city, in areas where the existing fire departments cannot provide the necessary fire service (Fig. 8). In this case, fire-rescue units can serve an average of 262.71 km^2 of the city's territory, which would increase fire service coverage by 5.1% and will cover 75.1% of the city's area.

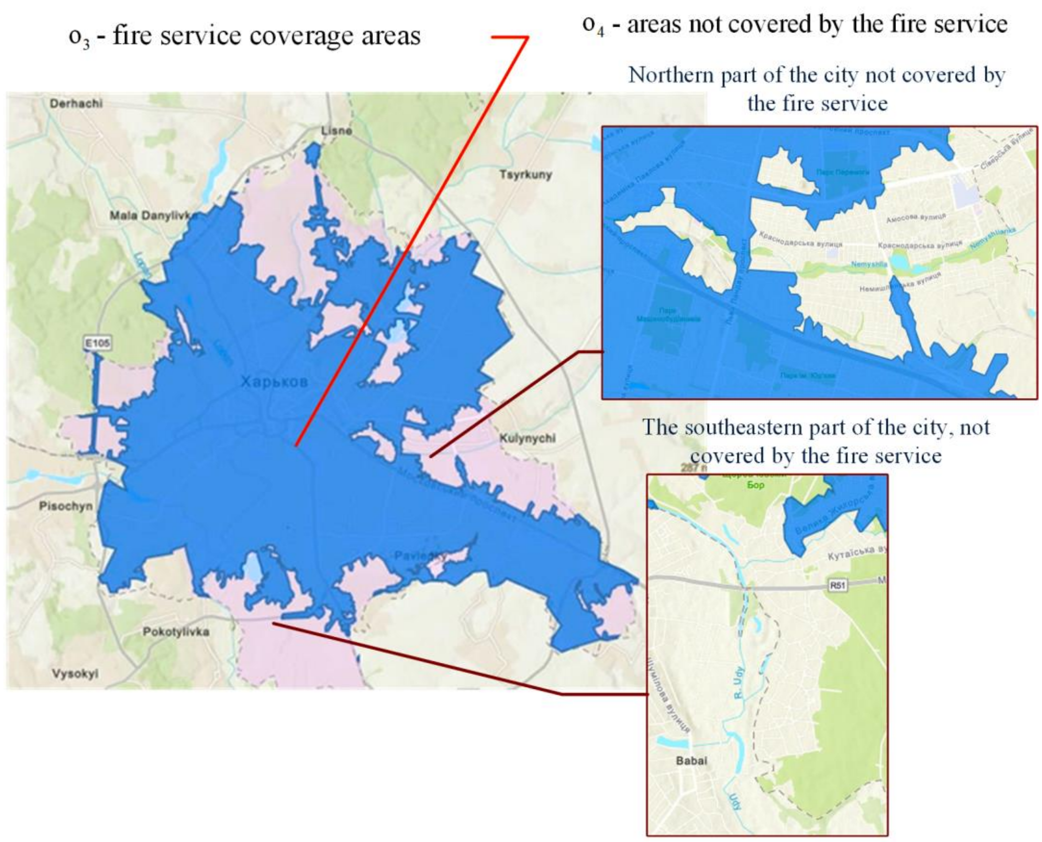

Fig. 7. Output shaping o_4 on operations a_2

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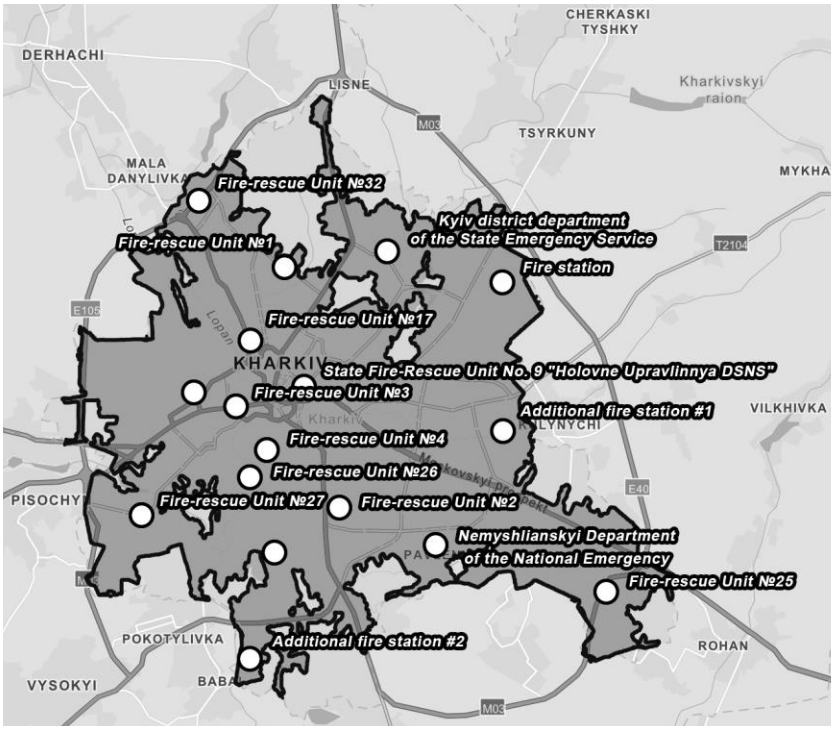

Fig. 8. Evaluation of the fire service coverage area considering the creation of additional fire-rescue units

3. Discussion

The presented results of the experiment using VGI showed the possibility of using the developed method in decision support systems when forming and improving the network of fire rescue units. At the same time, in the context of decentralization and implementation of the reform of the State Emergency Service, the proposed method provides additional tools for local governments. Based on the requirements of regulatory documents [2, 10], considering fire statistics and the current network configuration, the method combines information technology additional indicators, the need to consider which is confirmed by studies in countries such as China [3], Turkey [11], Australia [13], Canada [16], Chile [17], USA [21], India [23], and others. In particular, it is shown how the focus on response time [11], road traffic [14, 15], and availability of fire service [18] affect network improvement options. At the same time, considering the workload of fire stations helps not only to determine their reasonable number in a given area but also to justify the appropriate assignment of fire and rescue equipment. Identification of areas of the city that are not covered by the fire service makes it possible to strategically plan investments in infrastructure. The emphasis on the functional zoning of these areas allows tailor-made solutions, creating a network of integrated fire brigades consisting of professionals and volunteers, increasing the operational efficiency of emergency response. An analysis of the population density, available transport infrastructure, and road traffic makes it possible to identify ways to improve the dispatching policy. At the same time, the assessments obtained in the study show that with the help of the method within the information technology, it is possible to process large amounts of data, obtain valuable results, and adapt them to the real needs of the city.

Conclusions

The tasks of placing certain objects occupy a separate, actively developing direction, which, in addition to the development of mathematical science, contributes to the development of a new economic geography aimed at finding factors and incentives to improve the quality of life of the population [25]. In this regard, the classical problem of the “center-periphery” placement [27] was studied, the adaptation of which to the specifics of building and organizing a network of fire-rescue units of the city is aimed at minimizing the distance between the fire-rescue unit and the possible place of fire while maximizing fire service coverage.

As a tool for solving the adapted location problem, the methodology for studying information processes was further developed by refining the set-theoretic model of its information flows. Based on regulatory documents [2, 10] and agreeing with the conclusions of previous studies [9, 13, 23], a method for IT analysis of the urban network structure of fire-rescue units is proposed. It combines spatially distributed data from different sources and, considering the logic and dynamics of their interaction, explains the sequence of their processing and presentation to support decision-making when forming a network of fire-rescue units and finding ways to improve it, based on a set of possible improvement options.

The practical significance of the obtained results comes from the development of the structure of the prototype IT and its representation using data flow diagramming, which makes it possible to move on to the creation of information systems for analyzing the structures of fire-rescue units networks based on a set of spatial data. It increases the objectivity of decisions made when forming a city network of fire-rescue units.

The conducted experiment on studying the capabilities of the developed method showed its effectiveness in solving the classical problems of placing fire-rescue units, considering the accepted restrictions on their spatial accessibility.

Prospects for further research include correction of the data obtained in accordance with the current statistics of fires in the city, as well as considering the real resettlement of citizens and the actual development of the city.

Contribution of authors: review and analysis of references, **Svitlana Danshyna** and **Artem Nechausov**; development of conceptual provisions and methodology of research, **Svitlana Danshyna**; methodology results testing, **Artem Nechausov**; analysis of research results, **Svitlana Danshyna** and **Artem Nechausov**; writing original draft, **Svitlana Danshyna**; writing review and editing, **Artem Nechausov**; project administration, **Svitlana Danshyna**.

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МЕТОД ІНФОРМАЦІЙНОЇ ТЕХНОЛОГІЇ АНАЛІЗУ СТРУКТУРИ МЕРЕЖІ ПОЖЕЖНО-РЯТУВАЛЬНИХ ЧАСТИН МІСТА

Світлана Даншина, Артем Нечаусов

Предметом дослідження статті є процес аналізу структури мережі пожежно-рятувальних части міста в контексті оптимізації їх просторового розташування. **Метою** статті є підвищення об'єктивності рішень, що приймаються при формуванні міської мережі пожежно-рятувальних частин, шляхом розроблення методу інформаційної технології (ІТ) аналізу її структури за просторово-розподіленими даними. **Завдання:** для пошуку шляхів підвищення рівня пожежної безпеки міста проаналізувати існуючі підходи до формування мережі пожежно-рятувальних частин; з урахуванням особливостей побудови та організації мережі адаптувати класичну задачу про розміщення; запропонувати метод її розв'язку для мінімізації відстані між пожежною частиною та можливим місцем виникнення пожежі при забезпеченні максимальної зони охоплення території пожежним сервісом; розробити структуру ІТ для його реалізації на базі моделі інформаційних потоків процесу аналізу мережі пожежно-рятувальних частин з використанням геопросторового підходу. **Отримано такі результати**. Дослідження класичної задачі про розміщення та її адаптація до реальних завдань, які виникають при аналізі міської мережі пожежно-рятувальних частин, надали змогу подати мережу як сукупність незалежних дводольних графів. Для пошуку місця розташування вузлів мережі при розв'язанні адаптованої задачі розроблено метод ІТ, що, базуючись на *p*- медіанній моделі, поєднує авторську методологію дослідження інформаційних процесів та методи геопросторового аналізу. Узагальнюючи вимоги законодавства, сформовано множини вхідних і вихідних даних для ІТ і множину її операцій. Подання структури ІТ у вигляді діаграми потоків даних пояснює, як обробляють та узагальнюють сукупність факторів при формуванні рішень про створення та/або удосконалення наявної пожежної охорони міста. **Висновки**. Результати бібліографічного пошуку підтверджують необхідність урахування просторових особливостей місцевості, де планують створювати пожежно-рятувальну частину, а також просторову конфігурацію мережі наявних пожежних депо міста з оцінюванням її ефективності за інтегрованим показником. Це потребує розроблення спеціалізованих методів, орієнтованих на використання геоінформаційних систем для впровадження їх у системи прийняття рішень. Розроблено науково-методичне забезпечення для ІТ, яке надає органам місцевого самоврядування інструмент для аналізу пожежної безпеки міста з метою створення та/або удосконалення наявної пожежної охорони. Проведений експеримент по дослідженню можливостей запропонованого методу на основі добровільної географічної інформації по м. Харкову підтвердив ефективність його використання для розв'язання класичних задач про розміщення за умови прийнятих обмежень на просторову доступність пожежно-рятувальних части. Визначено додаткові можливості по удосконаленню мережі пожежно-рятувальних части з урахуванням їх просторового розподілу, завантаженості, доступності та отриманих зон охоплення / неохоплення пожежним сервісом. Наприклад, здійснено оцінювання зони охоплення пожежним сервісом наявною мережею пожежно-рятувальних частин. За регламентований час її значення сягає 70% від площі Харкова та залежно від реального дорожнього трафіку може коливатися в межах від 64.61% до 73.44%. Проілюстровано, що створення двох додаткових пожежно-рятувальних частин на півночі та півдні міста Харкова дає змогу збільшити зону охоплення майже на 5%, в середньому збільшуючи її до 75.1%.

Ключові слова: *p*-медіана модель; геопросторовий аналіз; модель інформаційних потоків процесу; IDEF0-модель; діаграма потоків даних; зона охоплення пожежним сервісом.

Даншина Світлана Юріївна – д-р техн. наук, проф. каф. геоінформаційних технологій та космічного моніторингу Землі, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Нечаусов Артем Сергійович – канд. техн. наук, доц. каф. геоінформаційних технологій та космічного моніторингу Землі, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Svitlana Danshyna – Doctor of Engineering Sciences, Professor at the Department of Geo-information Technologies and Space Monitoring of the Earth, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: s.danshyna@khai.edu, ORCID: 0000-0001-7354-4146.

Artem Nechausov – PhD in Information Technologies, Associate Professor at the Department of Geo-information Technologies and Space Monitoring of the Earth, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: a.nechausov@khai.edu, ORCID: 0000-0001-7216-5566.