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Multi-Objective Emergency Service Facility Location Problem Based on Fuzzy TOPSIS

Gia Sirbiladze*, Bezhan Ghvaberidze*, Bidzina Matsaberidze*, Anna Sikharulidze*

* *Faculty of Exact and Natural Sciences, Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia*

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ABSTRACT. This paper presents the construction of a new model for the fuzzy facility location problem. A fuzzy TOPSIS approach for formation and representing of expert's knowledge on the parameters of emergency service facility location planning is developed. A new objective function is constructed, which is the maximization of centers' selection ranking index. This function together with the second objective function - minimization of number of selected centers creates the multi-objective facility location set covering problem. The approach is illustrated by the simulation example of emergency service facility location planning for a city in Georgia. More exactly, the example looks into the problem of planning fire stations locations to serve emergency situations in specific demand points – critical infrastructure objects. *© 2017 Bull. Georg. Natl. Acad. Sci.*

Key words: emergency service facility location planning, fuzzy TOPSIS, critical infrastructure

Timely servicing from emergency service centers to the affected geographical areas (demand points, for example, critical infrastructure objects) is a key task of the emergency management system. Scientific research in this area focuses on distribution networks decision-making problems, which are known as a Facility Location Problem (FLP) [1,2]. FLP's models have to support the generation of optimal locations of service centers in complex and uncertain situations. There are several publications about application of fuzzy methods in the FLP. However, all of them have a common approach. They represent parameters as fuzzy values (triangular fuzzy numbers and others)[3,4] and develop methods for facility location problems called Fuzzy Facility Location Problem in this case (FFLP) [5,6]. In this work we consider a new model of FFLP based on the fuzzy TOPSIS approach [7,8] for the optimal selection of facility location centers.

Definition 1[3]: $\tilde{c}(t): R^1 \to [0;1]$ is called the Fuzzy Number (FN):

$$\tilde{c}(t)=\begin{cases} 1 & if \;\; t\in[c_2';c_2''] \\ \dfrac{t-c_1}{c_2'-c_1} & if \;\; t\in[c_1,c_2'] \\ \dfrac{c_3-t}{c_3-c_2''} & if \;\; t\in[c_2'',c_3] \\ 0 & otherwise \end{cases},$$

where $c_1 \le c_2' \le c_2'' \le c_3 \in R^1$ ($\tilde{c} \equiv (c_1, c_2', c_2'', c_3)$). Fuzzy number can be considered as a generalization of the interval number.

Let us review arithmetic operations on the triangular FN (TFN) ($c_2' = c_2''$). Let $\tilde{c}$ and $\tilde{b}$ be two TFNs, where $\tilde{c} = (c_1, c_2, c_3)$ and $\tilde{b} = (b_1, b_2, b_3)$. Then 1: $\tilde{c} + \tilde{b} = (c_1 + b_1, c_2 + b_2, c_3 + b_3)$; 2: $\tilde{c} - \tilde{b} = (c_1 - b_3, c_2 - b_2, c_3 - b_1)$; 3: $\tilde{c} \times k = (kc_1,\ kc_2, kc_3),\ k > 0$; 4: $\tilde{c}^k = (c_1^k, c_2^k,\ c_3^k),\ k > 0, c_i > 0$ 5: $\tilde{c} \cdot \tilde{b} = (c_1 b_1, c_2 b_2, c_3 b_3), c_i > 0, b_i > 0$ 6: $1/\tilde{b} = \{1/b_3, 1/b_2, 1/b_1\},\ b_i > 0$; 7: $\tilde{c} > \tilde{b}$ *if* $c_2 > b_2$ and *if* $c_2 = b_2$ *then* $\tilde{c} > \tilde{b}$ *if* $c_1 + c_3 > b_1 + b_3$, *otherwise* $\tilde{c} = \tilde{b}$. 8. The distance between two fuzzy numbers $d(\tilde{c}, \tilde{b}) = \sqrt{1/3[(c_1 - b_1)^2 + (c_1 - b_1)^2 + (c_1 - b_1)^2]}$. 9. If $\tilde{c} = (c_1, c_2, c_3)$ is TFN, then the expected value of $\tilde{c}$ is defined by the formula $E(\tilde{c}) = c_2 + (c_3 - 2c_2 + c_1)/4$.

Fuzzy TOPSIS Approach for the Selection of Facility Location Centers

Location planning for candidate centers is vital in minimizing traffic congestion arising from facility movement in extreme environment. In recent years, transport activity has grown tremendously and this has undoubtedly affected the travel and living conditions in difficult and extreme urban areas. Considering the growth in the number of freight movements and their negative impacts on residents and the environment, municipal administrations are implementing sustainable freight regulations like restricted delivery timing, dedicated delivery zones, congestion charging etc. With the implementation of these regulations, the logistics operators are facing new challenges in location planning for service centers. For example, if service centers are located close to customer locations, then they increase traffic congestion in the urban areas. If they are located far from customer locations, then the service costs for the operators result will be very high. Under these circumstances, it is clear that the location planning for service centers in extreme environment is a complex decision that involves consideration of multiple attributes like maximum customer coverage, minimum service costs, least impacts on geographical points' residents and the environment, and conformance to freight regulations of these points.

At first, we are focusing on a multi-attribute decision making approach for location planning for service centers under uncertain and extreme environment. We develop a fuzzy multi-attribute decision-making approach for the service center location selection problem for which a Fuzzy TOPSIS approach is used.

Let us assume that $A = \{a_1, a_2, ..., a_m\}$ is the set of all demand points (customers) and $S = \{s_1, s_2, ..., s_n\}$ is the set of all candidate centers, where we can locate service facilities. Let $\Omega = \{\mu_1, \mu_2, ..., \mu_l\}$ be the set of all attributes, which define center selection. Let $W = \{w_1, w_2, ..., w_l\}$ be the weights of attributes. For each expert e_k from invited group of experts $E = \{e_1, e_2, ..., e_t\}$, let r_{ij}^k be the rating of his evaluation for each candidate center s_i, $(i = 1, ..., n)$, with respect to each attribute μ_j, $(j = 1, ..., l)$. For the expert e_k we construct binary relation $\tilde{R}_k = \{r_{ij}^k,\ i = 1, ..., n;\ j = 1, ..., l\}$, elements of which are represented in TFNs. Our task is to build fuzzy TOPSIS approach, which for each candidate center s_i, $(i = 1, ..., n)$ aggregates presented objective and subjective data into scalar values - centers' selection ranking index. This aggregation formally can be represented as:

Table 1. Linguistic terms for candidate center ratings

Linguistic term	Ratings in TFNs
Very poor (VP)	(1,1,3)
Poor (P)	(1,3,5)
Fair (F)	(3,5,7)
Good (G)	(5,7,9)
Very good (VG)	(7,9,9)

Table 2. Linguistic terms for attribute ratings

Linguistic term	Ratings in TFNs
Very low (VL)	(1,1,3)
Low (L)	(1,3,5)
Medium (M)	(3,5,7)
High (H)	(5,7,9)
Very high (VH)	(7,9,9)

Table 3. Example of attributes for location centers selection

Attributes	Definition	Attributes type
Accessibility (ω_1) ω_1)	Access by public and private transport modes to the location	Benefit (the more the better)
Security (ω_2)	Security of the location from accidents, theft and vandalism	Benefit (the more the better)
Connectivity to multimodal transport (ω_3)	Connectivity of the location with other modes of transport, e.g. highways, railways, seaport, airport etc.	Benefit (the more the better)
Costs (ω_4)	Costs in acquiring land, vehicle resources, drivers and etc. for the location	Cost (the less the better)
Environmental impact (ω_5)	Impact of location on the environment, for example, air pollution, noise	Cost (the less the better)
Proximity to customers (ω_6)	Distance of location to customer locations	Benefit (the more the better)
Proximity to suppliers (ω_7)	Distance of location to supplier locations	Benefit (the more the better)
Resource availability (ω_8)	Availability of raw material and labor resources in the location	Benefit (the more the better)
Conformance to sustainable freight regulations (ω_9)	Ability to conform to sustainable freight regulations imposed by municipal administrations for e.g. restricted delivery hours, special delivery zones	Benefit (the more the better)
Possibility of expansion (ω_{10})	Ability to increase size to accommodate growing demands	Benefit (the more the better)

$$¢_i \equiv ¢(s_i) = Agregg(\Omega, W, \Pi, [\tilde{R}_k]_i, k = 1,...,t) \quad, i = 1,...,n.$$

In fuzzy set theory [3,4], conversion scales are applied to transform the linguistic terms into fuzzy numbers. In our approach, we apply a scale of 1–9 for rating the attributes and the candidate centers (alternatives). Table 1 presents the linguistic variables and fuzzy ratings for the alternatives and Table 2 presents the linguistic variables and fuzzy ratings for the attributes.

The proposed framework of location planning for candidate centers comprises four steps:

Step 1: Selection of location attributes involves the selection of location attributes for evaluating potential locations for candidate centers. These attributes are obtained from literature review, and discussion with experts and members of the city transportation group. For example, 10 attributes (see Table 3) are presented to determine the best location for implementing service centers.It can be seen in Table 3 that attribute μ_3 and attribute μ_4 belong to the cost category, that is, the lower the value, the more preferable the alternative for the best location. The remaining attributes are benefit type attributes, which means the higher the value, the more preferable the alternative is for selection.

Step 2: Selection of candidate location centers. Involves selection of potential locations for implementing service centers. The decision makers use their knowledge, prior experience with the transportation or other conditions of the geographical area of extreme events and the presence of sustainable freight regulations to identify candidate locations for implementing the service centers. For example, if certain areas are restricted for delivery by municipal administration, then these areas are barred from being considered as potential locations for implementing urban service centers. Ideally, the potential locations are those that cater to the interest of all city stakeholders, which are city residents, logistics operators, municipal administrations etc.

Step 3: Locations evaluation using fuzzy TOPSIS. The third step involves evaluation of candidate location centers against the selected attributes (for example Table 3) using the technique called fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Situation). The TOPSIS approach chooses the alternative that is closest to the positive ideal solution and farthest from the negative ideal solution. A positive ideal solution is composed of the best performance values for each attribute whereas the negative ideal solution consists of the worst performance values. The various steps of new fuzzy TOPSIS are presented as follows:

Step 3.1. Assignment of ratings to the attributes and the candidate centers. Let $\tilde{R}_k = \{r_{ij}^k,\ i=1,...,n;\ j=1,...,l\}$ be the performance ratings of each expert $e_k\left(k=1,2,..,t\right)$ for each alternative (candidate center) $s_i\left(i=1,2,..,n\right)$ with respect to attributes $\mu_j\left(j=1,2,..,l\right)$ presented in triangular fuzzy numbers.

Step 3.2. Compute aggregate fuzzy ratings for the attributes and the candidate centers**.** If the fuzzy ratings of all experts are described as triangular fuzzy numbers $\tilde{q}^k = \left(q_1^k, q_2^k, q_3^k\right), k=1,2,...,t$, then the aggregated fuzzy rating is given by $\tilde{q} = \left(q_1, q_2, q_3\right)$, where

$$q_1 = \min_k\left\{q_1^k\right\},\quad q_2 = \frac{1}{t}\sum_{k=1}^{t} q_2^k,\quad q_3 = \max_k\left\{q_3^k\right\}.$$

If the fuzzy rating and importance weight of the k-th expert are $\tilde{r}_{ij}^k = \left(r_{ij1}^k, r_{ij2}^k, r_{ij3}^k\right)$ and $\tilde{w}_j^k = \left(w_{j1}^k, w_{j2}^k, w_{j3}^k\right),\ j=1,2,..,l$, respectively, then the aggregated fuzzy ratings $\left(\tilde{r}_{ij}\right)$ of alternatives with respect to each attribute are given by $\tilde{r}_{ij} = \left(r_{ij1}, r_{ij2}, r_{ij3}\right)$, where

$$r_{ij1} = \min_k\left\{r_{ij1}^k\right\},\quad r_{ij2} = \frac{1}{t}\sum_{k=1}^{t} r_{ij2}^k,\quad r_{ij3} = \max_k\left\{r_{ij3}^k\right\}.$$

The aggregated fuzzy weights $\left(\tilde{w}_j\right),\ j=1,...,l$ of attributes are calculated as $\tilde{w}_j = \left(w_{j1}, \mu_{j2}, \mu_{j3}\right)$ where

$$w_{j1} = \min_k\left\{w_{j1}^k\right\},\quad w_{j2} = \frac{1}{t}\sum_{k=1}^{t} w_{j2}^k,\quad w_{i3} = \max_k\left\{w_{j3}^k\right\}.$$

Step 3. 3. Compute the fuzzy decision matrix**.** The fuzzy decision matrix for the *candidate centers S* and the attributes Ω is constructed as follows:

$$\begin{array}{c|cccc} & \mu_1 & \mu_2 & & \mu_l \\ \hline s_1 & \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1l} \\ s_2 & \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2l} \\ & \cdots & \cdots & \cdots & \cdots \\ s_n & \tilde{r}_{n1} & \tilde{r}_{n2} & \cdots & \tilde{r}_{nl} \end{array}$$

Step 3.4. Normalize the fuzzy decision matrix**.** The raw data are normalized using a linear scale transformation to bring the various attributes scales onto a comparable scale. The normalized fuzzy decision matrix $\tilde{R}$ is given by $\tilde{R} = \left[\tilde{r}_{ij}\right]_{nl}, i = 1, 2, ..., n; j = 1, 2, ..., l$, where $\tilde{r}_{ij} = \left(\frac{r_{ij1}}{r_j^*}, \frac{r_{ij2}}{r_j^*}, \frac{r_{ij3}}{r_j^*}\right)$ and $r_j^* = \max_i r_{ij3}$ (benefit attributes); $\tilde{r}_{ij} = \left(\frac{r_j^-}{r_{ij3}}, \frac{r_j^-}{r_{ij2}}, \frac{r_j^-}{r_{ij1}}\right)$ and $r_j^- = \min_i r_{ij1}$ (cost attributes).

Step 3.5. Compute the weighted normalized fuzzy decision matrix. The weighted normalized matrix $\tilde{V}$ for the attributes is computed by multiplying the weights $\left(\tilde{w}_j\right)$ of evaluation attributes with the normalized fuzzy decision matrix $\tilde{r}_{ij}$: $\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxl}, i = 1, 2, ..., n; j = 1, 2, ..., l$ where $\tilde{v}_{ij} = \tilde{r}_{ij}\left(\cdot\right)\tilde{w}_j$.

Step 3.6. Compute the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS).The FPIS and FNIS of the candidate centers are computed as follows:

$A^* = \left(\tilde{v}_1^*, \tilde{v}_2^*, ..., \tilde{v}_l^*\right)$ $A^- = \left(\tilde{v}_1^-, \tilde{v}_2^-, ..., \tilde{v}_l^-\right)$ where $\tilde{v}_j^* = \max_i \left\{v_{ij3}\right\}$, $\tilde{v}_j^- = \min_i \left\{v_{ij1}\right\}$, $i = 1, 2, .., n;\ j = 1, 2, .., l$.

Step 3.7. Compute the distance of each candidate center's weighted normalized evaluations from FPIS and FNIS. These distances $\left(d_i^*, d_i^-\right)$ are computed as follows:

$$d_i^* = \sum_{j=1}^{l} d(\tilde{v}_{ij}, \tilde{v}_j^*), \quad d_i^- = \sum_{j=1}^{l} d(\tilde{v}_{ij}, \tilde{v}_j^-), \quad i = 1, 2, ..., n.$$

Step 3.8. Compute the closeness coefficient $\left(CC_i\right)$ of each candidate center. The closeness coefficient CC_i represents the distances to the fuzzy positive ideal solution $\left(A^*\right)$ and the fuzzy negative ideal solution $\left(A^-\right)$ simultaneously. The closeness coefficient of each candidate center s_i is calculated as

$$CC_i = d_i^- / (d_i^- + d_i^*), \quad i = 1, 2, ..., n .$$

Step 3.9. Rank the alternatives. Rank the alternatives (candidate centers) according to the closeness coefficient $\left(CC_i\right)$ in decreasing order and select the alternative with the highest closeness coefficient for final implementation. The best alternative is closest to the FPIS and farthest from the FNIS.

Definition 2: A selection ranking index of candidate center $s_i, i = 1, ..., n$ is called its closeness coefficient $\left(CC_i\right)$: $¢_i = CC_i$.

Multi-Objective Optimization Model of Fuzzy Facility Location Set Covering Problem

The location set covering problem (LSCP) was proposed by C. Toregas and C. Revell in 1972, which seeks a solution for locating the least number of facilities to cover all demand points within the service distance. In some of our works we are focusing on the multi-objective fuzzy set covering problems [9,10] for extreme conditions. Fuzzy extension of LSCP for facility location was given in [11]. In this work we construct new fuzzy LSCP model for emergency service facility location planning.

As we discussed in previous section, constructed Fuzzy TOPSIS technology forms center's selection rational ranking index. The center's ranking index reflects expert evaluations with respect to the center, considering all actual attributes. If $x=\{x_1,x_2,...,x_n\}$ is Boolean decision vector, which defines some selection from candidate centers $S=\{s_1,s_2,...,s_n\}$ for facility location, we can build centers' selection ranking index as linear sum of $\text{¢}_j x_j$ values: As a result, new objective function – *centers' selection ranking index* $\sum_{j=1}^{n}\text{¢}_j x_j$ is constructed. Maximizing it will select group of centers with the best total ranking index from admissible covering selections. Classical facility location set covering problem tries to *minimize the number of centers*, where service facilities can be located - $\sum_{j=1}^{n}x_j$. The problem aims to locate service facilities in minimal travel time from candidate centers. In extreme environment for emergency planning the radius of service center is not defined based on distance but it is defined based on maximum allowed time T for movement, since the rapid help and servicing is crucial for demand points in such situations. Respectively, a set of candidate centers N_i, covering customer $a_i,\ a_i\in A$, is defined as $N_i=\{s_j,\ s_j\in S\,/\,E(\tilde{t}_{ij})\le T\}$. Then we can state bi-objective facility location set covering problem:

$$\min \qquad z_1=\sum_{j=1}^{n}x_j \ \ (1), \quad \max \qquad z_2=\sum_{j=1}^{n}\text{¢}_j x_j \ (2)$$

$$\sum_{s_j\in N_i}x_j\ge 1\ \ (i=1,2,...,m);\quad x_j\in\{0,1\}\quad j=1,2,...,n.\ (3)$$

Numerical Simulation of Emergency Service Facility Location Model

We illustrate the effectiveness of the constructed optimization model by the numerical example. Let us consider an emergency management administration of a city in Georgia that wishes to locate some fire stations with respect to timely servicing of critical infrastructure objects. Assume that there are 6 demand points (critical infrastructure objects) and 5 candidate facility centers (fire stations) in the urban area. Let us have 4 experts from Emergency Management Agency (EMA) of Georgia for the evaluation of the travel times and the ranking indexes of candidate facility centers. The travel times between demand points and candidate centers are evaluated in triangular fuzzy numbers(see Table 4). According to the standards of EMA (Georgia), the principle of location fire stations is that the fire station can reach the area edge within 5 minutes after receiving the dispatched instruction. Therefore, we set covering radius T = 5 minutes.

Each expert $e_k\ (k=1,2,3,4)$ presented the ratings r_{ij}^k for each candidate center s_i, $(i=1,...,5)$, with

Table 4. Travel times from fire station to critical infrastructure objects (in minutes)

	a_1	a_2	a_3	a_4	a_5	a_6
s_1	(3,5,7)	(2,4,6)	(4,6,7)	(4,7,9)	(1,3,5)	(1,3,4)
s_2	(6,10,14)	(4,9,14)	(2,4,6)	(5,7,10)	(1,4,8)	(1,4,5)
s_3	(4,8,12)	(4,7,11)	(4,6,9)	(2,4,7)	(4,7,10)	(4,6,8)
s_4	(4,7,10)	(7,11,15)	(6,9,13)	(4,6,8)	(2,4,6)	(1,3,5)
s_5	(1,3,5)	(2,4,6)	(1,3,6)	(2,4,7)	(4,6,8)	(5,9,12)

respect to each attribute μ_j, $(j = 1,...,10)$ and weights $\tilde{w}_j^k$ for each candidate center (evaluations were presented in triangular fuzzy numbers and these data are omitted here). Using the algorithm of new fuzzy TOPSIS we calculated expected values of candidate centers' selection ranking indexes: $\text{¢}_1 = 0.82$, $\text{¢}_2 = 0.71$, $\text{¢}_3 = 0.79$, $\text{¢}_4 = 0.63$, $\text{¢}_5 = 0.86$. The expected values of fuzzy travel times $E(\tilde{t}_{ij})$ has been also calculated (Def.1). After these calculations a Combinatorial Programming Problem (1)-(3) has been constructed:

$$\begin{cases} f_1 = x_1 + x_2 + x_3 + x_4 + x_5 \Rightarrow \min, \\ f_2 = 0.82x_1 + 0.71x_2 + 0.79x_3 + 0.63x_4 + 0.86x_5 \Rightarrow \max \\ x_1 + x_5 \geq 1, \\ x_2 + x_5 \geq 1, \\ x_3 + x_5 \geq 1, \\ x_1 + x_2 + x_4 \geq 1, \\ x_i \in \{0,1\},\ i = 1,2,3,4,5. \end{cases}$$

For the constructed problem Pareto solutions are founded. There are:

$$a)\ x_1 = 1, x_5 = 1,\ f_1 = 2;\ f_2 = 1.68,\ b)\ x_1 = 1, x_2 = 1, x_5 = 1,\ f_1 = 3;\ f_2 = 2.39,$$

$$c)\ x_1 = 1, x_2 = 1, x_3 = 1, x_5 = 1,\ f_1 = 4;\ f_2 = 3.18,\ d)\ x_i = 1, i = 1,2,3,4,5,\ f_1 = 5,\ f_2 = 3.81.$$

It is clear that increasing of fire stations number in Pareto solutions gives us more better level of the second objective function - *fire stations' selection ranking index*. But the decision on the choice of the fire stations as service centers depends on the decision-making person's preferences with respect to risks of administrative actions.

Conclusions

The paper presented new approach for fuzzy facility location problem for selection of the locations of service centers in extreme and uncertain situations. The approach utilizes experts knowledge represented by fuzzy triangular numbers and considers the suitability of central location (i.e. affordability, security, etc.) using fuzzy TOPSIS approach. On the other hand, the model also considers the necessity to reach all critical infrastructure points and time that is required to reach them, also presented by fuzzy triangular numbers. As a results bi-objective set covering problem is obtained. The constructed approach is illustrated by a numerical example for locating fire stations servicing critical infrastructure points in a city in Georgia. For the constructed problem Pareto solutions are obtained. In our future studies (large dimension cases of the problem) the epsilon-constraint approach [12,13] for the Pareto front obtaining will be constructed.

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ინფორმატიკა

ფაზი-TOPSIS-ზე დაფუძნებული საგანგებო სიტუაციების ობიექტების განთავსების მრავალკრიტერიუმიანი ამოცანა

გ. სირბილაძე*, ბ. ღვაბერიძე*, ბ. მაცაბერიძე*, ა. სიხარულიძე*

** ივანე ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი, ზუსტ და საბუნებისმეტყველო მეცნიერებათა ფაკულტეტი, თბილისი, საქართველო*

(წარმოდგენილია აკადემიის წევრის მ. სალუქვაძის მიერ)

ნაშრომში მოცემულია ობიექტების განთავსების ამოცანის ახალი ფაზი-მოდელის აგება. განვითარებულია საგანგებო სიტუაციების ობიექტების განთავსების დაგეგმვის პარამეტრებზე ექსპერტის ცოდნის წარმოდგენისა და ფორმირების ფაზი-TOPSIS მიდგომა. შექმნილია ახალი მიზნობრივი ფუნქცია - ცენტრების შერჩევის რანჟირების ინდექსის მაქსიმიზაცია. ეს კი მეორე მიზნობრივ ფუნქციასთან - შერჩეული ცენტრების რაოდენობის მინიმიზაციასთან ერთად ქმნის მრავალკრიტერიუმიანი ობიექტების განთავსების ამოცანას. აგებული მოდელი ილუსტრირებულია დასახლებული პუნქტის საგანგებო სიტუაციაში დახმარების ობიექტების განთავსების დაგეგმვის სიმულაციურ მაგალითზე. კონკრეტულად კი, საგანგებო სიტუაციის შემთხვევაში თუ როგორ დაიგეგმოს სახანძრო სადგურების განთავსება კრიტიკული ინფრასტრუქტურის ობიექტების მოთხოვნების გათვალისწინებით.

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