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DETERMINATION OF THE GENERALIZED OPTIMALITY CRITERIA FOR SELECTING CIVILIAN SHELTER FACILITIES FROM ATTACKS BY BALLISTIC (CRUISE) MISSILES AND KAMIKAZE DRONES IN URBANIZED AREAS

V. YAKOVENKO, N. FURMANOVA, I. FLYS, O. MALYI, O. FARAFONOV, H. MOROZ

Abstract. The object of the study is the planning of the selection of civilian shelter from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas. A generalized model for assessing the choice of civilian shelter facilities has been developed by applying linear forms of factor linkage in combination with a generalized optimality criterion in the form of a linear combination of local criteria. The multivariate regression analysis method was chosen to study the correlation between the generalized criterion and the observed feature. A generalized criterion for the optimal choice of civilian shelter facilities from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas is calculated in the form of regression coefficients. The criterion can facilitate a simplified determination of the generalized indicator of a linear model for planning the protection of civilians in cities outside the area of hostilities. The initial data is a set of physical (technical) states of shelters with a list of values and features sufficient to assess their resistance to high dynamic loads.

Keywords: optimality criterion, civilian shelter facilities, weighting factor, missile attacks.

INTRODUCTION

The long-term evolution of the modern world hegemony of the rule of international norms and humanity has failed completely. It was completely levelled after the Russian Federation (RF) unleashed its so-called “aggression” against the sovereign state of Ukraine [1]. After all, a war in the centre of Europe on such a scale since the end of the Second World War is the trigger for the first shot of a new global war. Consequently, the dictators felt the complete amorphousness of global institutions, as well as the meaninglessness of any commitments and international treaties [2–4]. Thus, the beginning of Russia’s aggression against Ukraine was carried out using several indirect levers of pressure: political, financial and economic, media, human and military [5, 6]. Subsequently, hybridity grew into the so-called “special military operation” (SMO), a striking feature of which is a categorical violation of all international legal norms [7] and crimes against civilians. This raises the logical question of the safety of children, women, and the elderly living in peaceful towns and villages, but suffering from regular air attacks by enemy forces using cruise (ballistic) missiles and attack kamikaze drones.

The world has a vast experience of successfully solving various complex problems, but humanity is losing the war to brazen terrorism. The protection of civilians in urbanized areas that are not involved in hostilities remains a serious problem. Protecting ordinary citizens from missile and kamikaze drones attacks, developing infrastructure that will protect them not only from death but also from injury - these are questions that needed to be answered yesterday. It is necessary to immediately create a fund for protective structures throughout the country without exception.

Ukraine can learn from the experience of other countries. Israel, for example, has many mobile shelters [8], especially in cities with short daylight hours in the south in the form of bus stops or just separate blocks. The main types of Israeli shelters are:

- protected rooms (mamads), which in peacetime are used by Israelis as ordinary living quarters;
- a folding bomb shelter that can fit in a room and unfold in a few minutes in an apartment or house;
- strengthening socially important facilities, including bus stops and schools;
- temporary bell-shaped fortifications for a limited number of people that can be placed in open space or near roads;
- sewerage pipes as storage facilities, which are laid near houses in several-metre-long lines.

In addition, Israel has a concept of protected space in the form of places that were not designed as shelters, but can be used in the absence of better alternatives. In general, such places mean any premises that are separated from the street by more than two walls and do not have windows according to the rule of two walls. This can significantly reduce the number of casualties even in the context of mass attacks [9] and when using fragmentation and high-explosive shells that have a high degree of damage to objects [10–12]. Thus, there is real experience in protecting civilians from missile and UAV attacks. However, any country keeps its experience in planning the choice of defences secret. The impression that it is easy to choose certain protective structures is superficial, as, as a rule, separate unrelated local tasks are solved. There is no comprehensive approach to achieving the overall goal, so developing approaches to decision-making on the choice of civilian shelter facilities from missile and kamikaze drones attacks is an urgent task.

LITERATURE ANALYSIS AND PROBLEM STATEMENT

Global weapons manufacturers are increasingly paying attention to limiting the unexpected lethality of their weapons by “scalping” the enemy [13]. However, this does not apply to the military and political leadership of the Russian Federation. In the current realities of the so-called undeclared wars, civilians are an integral part of these confrontations, and the use of UAVs for inflicting damage is constantly increasing.

Article [14] discusses the current threats of kamikaze dronesand methodologies for assessing these threats, and proposes modelling the UAV threat through an attack protection tree. Study [15] analyses in depth the use of UAVs in modern confrontations and cyberattacks, and considers countermeasures based on the technical limitations and shortcomings of the aircraft. However, these works do not address the issue of assessing the protection of shelter facilities.

Civilian sheltering facilities play an important role in protecting people from enemy aggression and should therefore be considered an effective security measure. The article [16] discusses some strategic considerations of passive protection in the design and planning of urban shelters, in particular for countries with a critical strategic and sensitive location and exposed to threats from expansionist states. A comprehensive analysis of shelters, taking into account their actual state, is proposed in [17]. In 2022, the State Fire Service of Poland conducted an inventory of shelters for the population and posted an app with information on their location and class. However, the authors note that the created database is incomplete and often the data provided is not true. Therefore, it is proposed to create an interdepartmental group of professionals to develop criteria for assessing the suitability and protection of shelters from various types of impacts (military operations, man-made accidents, environmental disasters, etc.).

Israel's use of civilian shelter facilities is a part of a defence system, another component of which is the Iron Dome, a missile defence system deployed around Israel's major urbanized areas. It was created to provide citizens with greater protection from enemy missile attacks. The study [18] examined how civilians' experience with the Iron Dome system affects their perceptions of its reliability, their trust in it, their attitudes towards enemy missile alerts, and their decision to stay in the ADS. Although the study takes into account various indicators of reliability, the focus is on the perception of the proposals from the automated decision-making system by the population.

A similar issue is raised by [19], which analyses the results of the erroneous perception of the probability of being hit by ballistic missiles, as demonstrated by the operator of an automated air defence system. This study confirms the need to develop a comprehensive approach to threat assessment and recommendations for actions without or with minimised operator involvement.

A major study [20] was commissioned by the United States Air Force Europe (USAFE). It addresses a number of issues related to protection against cruise and ballistic missiles and UAVs, including the analysis of shelters and recommendations for their modernisation. However, the work is analytical in nature and does not raise the issue of collecting general information and selecting the optimal civilian shelter facilities.

The importance of research on the development of decision support systems is confirmed by [21], which describes an experiment on the implementation of such a system within a defence operation. However, the modelling is based on the results of a reconnaissance model of UAVs, which is the subject of a significant part of the paper.

Thus, there are many works that solve individual problems of using civilian shelter facilities from missile and kamikaze drones attacks, but there is no comprehensive approach to achieving the overall goal. Therefore, there is a need to develop a methodological approach to analysing the initial data with the selection of an optimality criterion. It should approximate the determination of the generalisation of the indicator of the linear planning model for selecting facilities of sheltering the civilian population from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the study is to develop a mathematical approach that will improve the efficiency and accuracy of decision-making on the choice of civilian shelter facilities from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas. This will provide an opportunity to improve the safety of civilians in cities and towns outside the combat zone.

The following tasks were set to achieve this goal:

- to develop a generalised model for assessing the selection of civilian shelter facilities against attacks by ballistic (cruise) missiles and kamikaze drones s in urbanized areas;
- determine the vectors of weighting coefficients of the proposed model;
- to justify the choice of a method for studying the correlation between a generalised criterion and an observable feature.

MATERIALS AND METHODS OF RESEARCH

The object of the study is to plan the choice of civilian shelter facilities from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas. The essence of the proposed approach is to adapt the existing mathematical apparatus to the real conditions of operational decision-making by applying a generalised optimality criterion. The weighting criteria make it possible to determine how relevant individual means are in a particular situation, which will increase the efficiency of planning the selection of the civilian shelter facilities.

The following research methods were chosen:

- generalization — to formulate an indicator of a linear model for planning the protection of civilians from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas;
- classification — to identify and substantiate the main factors affecting the feasibility of using and the effectiveness of the protective properties of the protective equipment in a given situation;
- analysis — to determine the criteria that can be used when deciding on the choice of civilian shelter facilities from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas;
- regression analysis — to study the correlation between the generalised criterion and the observed feature;
- synthesis — to develop a model for assessing the effectiveness of civilian shelter facilities.

The mathematical modelling was carried out using ASNA software (Ukraine), which provides a formalised representation of the structure and behaviour of a system engineering object.

RESULTS OF RESEARCH ON THE MATHEMATICAL APPARATUS FOR ASSESSING THE EFFECTIVENESS OF CIVILIAN SHELTER FROM MISSILE AND UAV ATTACKS

Development of a generalised model for assessing the choice of shelter from missile and UAV attacks

Decisions on the choice of civilian shelter should be made taking into account all the above criteria and in accordance with national and international standards. The standards for this type of structure should also be taken into account.

The optimal criteria for the selection of a civilian protective structure may vary depending on the specific conditions and missile attacks. However, in general, there are several criteria that can be used when deciding on the selection of civilian protective equipment:

- effectiveness of civilian shelter facilities: it is important that the type of structures and method of their application are designed to protect people without injury or maim from the fragmentation and blast effects of ballistic (cruise) missiles and enemy UAVs;
- minimizing collateral damage during relocation to a shelter: it is important to take into account possible collateral damage based on the density of civilian areas and the availability of convenient routes to access protective shelters;
- minimizing collateral damage in the event of a direct hit by both aircraft and their bulky fragments after being shot down by air defence forces. It is important to take into account possible cases of hitting these structures and provide them with medical supplies to provide first aid to the victims. It is also advisable to place signalling devices to notify the State Emergency Service and medical teams of damage to the civilian shelter facilities;
- consideration of the specifics of the environment in urbanised areas. Consideration should be given to the weather, time of day, terrain, built-up and illumination of the area, the presence of parked cars on the way to the civilian shelter facilities, the average length of the journey and other conditions that may impede rapid movement;
- cost-effectiveness: the cost of sheltering civilians, the ability of industry to meet the needs of the population in a short time, and the cost of their maintenance and upkeep should be taken into account.

In general, the choice of civilian shelter in urbanized areas should be based on tools that can describe the degree of realisation of their potential capabilities (Fig. 1).

The analysis of Fig. 1 indicates a factor that affects the optimisation of decisions. This may be the so-called wide range of protective structures from various manufacturers. However, its main role is to implement simple concepts — preserving not only civilian lives, but also health in the full sense of the word. After all, the existing standards are more general [22] and do not fully reveal the essence of protecting citizens from missile threats [23] or the threat of using kamikaze drones . Therefore, in order to determine the criterion for the optimal selection of an air defence system against attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas, it is necessary to understand the relationship between the nature of the attacks and the capabilities of the civilian shelter facilities. For the practical implementation of the above, it is possible to use linear forms of factor relationship in combination with a generalised optimality criterion in the form of a linear combination of local criteria [24–26]:

$$F(x)=a_1 f_1(x)+\ldots+a_i f_i(x)+\ldots+a_K f_K(x), \quad (1)$$

where a_i are the weighting coefficients for local optimality criteria; *i* is the index of the local criterion $(1, 2, \ldots, K)$.

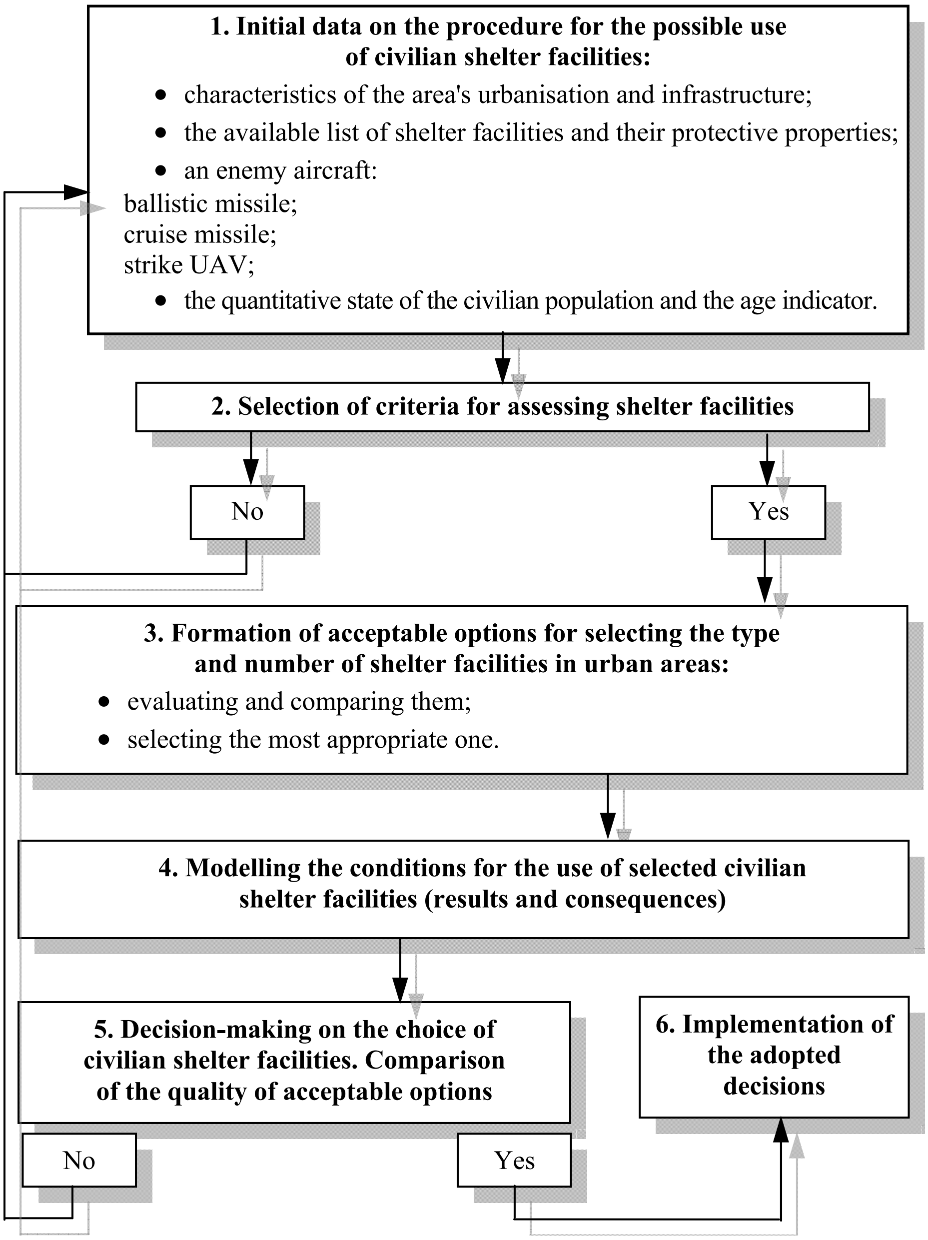

Fig. 1. Flowchart of the model for assessing the effectiveness of the use of civilian shelter facilities

Determination of the weighting vectors of the proposed model

To determine the vector $\overline{a}$ of weighting coefficients, it is possible to apply an approach with the selection of a certain local criterion as an indicator (basic optimality criterion) $f_i(x)$. Then, the dependence of the remaining criteria $(K-1)$ on the given one can be represented as [27; 28]:

$$f_i(x) = a_1^* f_1(x) + \ldots + a_{i-1}^* f_{i-1}(x) + a_{i+1}^* f_{i+1}(x) + \ldots + a_K^* f_K(x). \qquad (2)$$

Based on the method of multivariate regression analysis and using dependence (2), $\overline{a}^0$ will look like this [29–31]:

$$f_i(x)=a_1^0 f_1(x)+...+a_{i-1}^0 f_{i-1}(x)+a_{i+1}^0 f_{i+1}(x)+...+a_K^0 f_K(x).$$

Then the optimisation criterion in the linear model will be applied in the following interpretation:

$$F(x)=f_i(x)=a_1^0 f_1(x)+...+a_{i-1}^0 f_{i-1}(x)+a_{i+1}^0 f_{i+1}(x)+...+a_K^0 f_K(x).$$

Some local criteria $k_1 < k$ (time to move to shelters) should be minimised as much as possible, and the rest (number of civilian shelter facilities, their degree of protection) should be maximised:

$$F(x) = -\sum_{i=1}^{k_1} a_i^0 f_i(x) + \sum_{i=k_1+1}^{K} a_i^0 f_i(x) \to \max,$$

either:

$$F(x) = \sum_{i=1}^{k_1} a_i^0 f_i(x) - \sum_{i=k_1+1}^{K} a_i^0 f_i(x) \to \min.$$

This approach is associated with the rapidity and unpredictability of attacks, as well as possible sudden changes in the situation.

Selecting a method for studying the correlation between a generalised criterion and an observable feature

To study the effectiveness of the relationship between the generalised criterion $F(x)$ and the observational feature f_i $(i=\overline{1,K})$ as the weighting factor a_i $(i=\overline{1,K})$ of the function of the form (2), it is possible to apply the method of multivariate regression analysis:

$$F(x,a) = a_0 + a_1 f_1(x) + ... + a_j f_j(x) + ... + a_m f_m(x),$$

where *m* is the number of parameters under study, *units*.

In this case, the level of regression is described by the values of $a_0, a_1, \ldots, a_m$ and the final variance. Replacing the values of $a_0, a_1, \ldots, a_m$ with their estimates, and $f_j(x)$ with f_j, the regression equation will take the form:

$$F(x) = b_0 + b_1 f_1 + ... + b_j f_j + ... + b_m f_m.$$

The initial data for calculating the coefficients $b_0, \ldots, b_m$ are a sample from a multidimensional population in the form of the matrix f and the vector $\overline{F}$ [32–34]:

$$f = \begin{vmatrix} f_{11} & f_{21} & f_{j1} & f_{m1} \\ f_{12} & f_{22} & f_{j2} & f_{m2} \\ \cdots & \cdots & \cdots & \cdots \\ f_{1n} & f_{2n} & f_{jn} & f_{mn} \end{vmatrix}, \quad \overline{F} = \begin{vmatrix} F_1 \\ F_2 \\ \cdots \\ F_n \end{vmatrix}.$$

For the convenience of selecting the civilian shelter facilities through $\bar{f}_j$, it is advisable to define the *j*-th vector as the column f of the matrix

$\bar{f}_j = \{f_{j1}, f_{j2}, ... f_{jn}\}$, and through $\bar{f}_i$ to calculate the *i*-th vector as a row of the corresponding matrix $\bar{f}_i = \{f_{1i}, f_{2i}, ..., f_{mi}\}$:

$$\begin{cases} nb_0 + b_1 \sum_{i=1}^{n} f_{1i} + ... + b_m \sum_{i=1}^{n} f_{mi} = \sum_{i=1}^{n} F_i; \\ b_0 \sum_{i=1}^{n} f_{1i} + b_1 \sum_{i=1}^{n} f_{1i} f_{1i} + ... + b_m \sum_{i=1}^{n} f_{1i} f_{mi} = \sum_{i=1}^{n} f_{1i} F_i; \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ b_0 \sum_{i=1}^{n} f_{mi} + b_1 \sum_{i=1}^{n} f_{1i} f_{mi} + ... + b_m \sum_{i=1}^{n} f_{mi} f_{mi} = \sum_{i=1}^{n} f_{mi} F_i. \end{cases} \quad (3)$$

Despite the fact that this system can be calculated by any method of linear algebra, in conditions of limited time indicators, the inverse matrix method can be used when selecting civilian shelter facilities, expressing through b_j $(j = 1, 2, \dots, m)$ [35–37].

Substituting the equation of the form (3) into the other expressions of the system, we define the coefficient matrix by C with the unknown parameters $b_1, b_2, \dots, b_m$ and the substitution of b_0. The inverse matrix can be defined by C^{-1}, respectively, the element located at the intersection of the *i-th* row and the *j-th* column by c_{ij}^{-1}:

$$b_j = \sum_{i=1}^{n} c_{ij}^{-1} (f_{ji} F_i - n\bar{f}_j \bar{F}). \quad j = 1, 2, ..., m, \quad b_0 = \bar{F} - b_1 \bar{f}_1 - ... - b_j \bar{f}_j - ... - b_m f_m.$$

The estimate of the final variance s_{qp}^2 is the expression:

$$s_{KH}^2 = \frac{\sum_{i=1}^{n} [F_i - F(f_i)]^2}{n - m - 1},$$

where F_i is the measured value of the performance attribute; $F(f_i)$ is the value of the outcome variable calculated according to the regression equation.

To statistically substantiate the conclusion $t = \left| \frac{b_j}{s_{b_j}} \right|$ each of the coefficients $(j = 0, 1, 2, ..., m)$ is different from zero (significance of the regression coefficient estimates) and is calculated by the expression [38, 39]:

$$\begin{cases} s_{b_0} = \dfrac{s_{KH}}{\sqrt{\dfrac{1}{n} + \sum_{j,k=1}^{n} \bar{f}_j \bar{f}_k c_{ij}^{-1}}}, \\ s_{b_j} = \dfrac{s_{KH}}{\sqrt{c_{jj}^{-1}}}, \end{cases} \quad i = 1, 2, ..., n, \quad j \neq k. \quad (4)$$

In accordance with the given significance level χ and the number of degrees of freedom $k = n - m - 1$, the critical value of $t_{\chi k}$ is as follows:

$t > t_{\chi k}$, the null hypothesis that the regression coefficient is equal to zero is rejected and considered significant;

$t < t_{\chi k}$, the estimate of the regression coefficient will be insignificant.

Due to the regression analysis, the expression for the generalised optimality criterion will be as follows:

$$F(x) = b_0 + b_1 f_1(x) + \ldots + b_{m'} f_{m'}(x),$$

where $m' < m$ — regression coefficients may be insignificant.

The multivariate regression analysis method was chosen due to its following advantages:

- allows for easy interpretation of the impact of individual independent variables on the dependent variable; regression coefficients help to understand how much the dependent variable changes when the unit of the independent variable changes, while holding other variables constant;
- linear regression is a relatively simple and well-studied model, which makes it a reasonable choice for the first analysis of data;
- If the relationship between the variables is basically linear, then linear regression can provide fairly accurate results;
- it can help to identify statistically significant relationships between variables and highlight important factors;
- it is possible to analyze the influence of one factor while others are fixed, which helps to understand how variables interact with each other.

To conduct the analysis, it is proposed to determine the values of the weighting coefficients for various attributes (Table).

Characteristics and common features of the object influencing on results

Type	Characteristics and common features
Characteristics of urbanized areas	local centre
	centre of the periphery
	commercial district
	residential area
	industrial area
	neighbourhood
Planning of urban streets and their importance	rectangular
	radiated
	beam
	beam-ring
	contour shaped
	wrong
	combined planning
	linear
Characteristics of buildings by size	small buildings (area is less than 180 m^2)
	medium-sized buildings (area from 180 m^2 to 2000 m^2)
	large buildings (area from 2000 m^2 to 4000 m^2)
	massive buildings (area exceeds 4000 m^2)
Characteristics of buildings by height	low-rise (up to 3 floors inclusive, with a building height of up to 9 m)
	multi-storey (up to 9 floors inclusive, with a building height of 9 m to 26.5 m)
	Increased-storey (up to 16 floors inclusive, with a height of 26.5 m to 47 m)
	high-rise (more than 16 floors, with a height of more than 47 m)

Continued Table

<table>
<tr><th>Type</th><th colspan="3">Characteristics and common features</th></tr>
<tr><td rowspan="6">Construction materials</td><td colspan="3">Wood</td></tr>
<tr><td colspan="2" rowspan="2">Brick</td><td>Brick buildings</td></tr>
<tr><td>Buildings with box walls</td></tr>
<tr><td colspan="3">Reinforced concrete</td></tr>
<tr><td colspan="2" rowspan="2">Steel or metal</td><td>Frame houses with heavy walls</td></tr>
<tr><td>Frame houses with lightweight walls</td></tr>
<tr><td rowspan="7">Type of facilities that can be used as a civilian shelter</td><td colspan="2" rowspan="2">Special purpose buildings</td><td>Storage</td></tr>
<tr><td>Anti-radiation (anti-chemical) shelter</td></tr>
<tr><td colspan="3">Dual-purpose buildings</td></tr>
<tr><td colspan="3">Prefabricated modular civil defence structures</td></tr>
<tr><td colspan="3">Rapidly built modular storage facilities</td></tr>
<tr><td colspan="3">External enclosing structures of modular type prefabricated radiation protection shelters</td></tr>
<tr><td colspan="3">The simplest shelters</td></tr>
<tr><td rowspan="10">An enemy aircraft</td><td rowspan="10">Ballistic missile (rocket)
Cruise missile
Strike UAV</td><td rowspan="2">Initial effect of the explosion</td><td>light flash</td></tr>
<tr><td>sound effect</td></tr>
<tr><td rowspan="5">Impact of the explosion (impact on surrounding infrastructure)</td><td>Brisant effect</td></tr>
<tr><td>blast effect</td></tr>
<tr><td>thermal effect</td></tr>
<tr><td>fragmentation effect</td></tr>
<tr><td>Secondary fragmentation effect of the destroyed object (breaking up the fragmentation mass of the aircraft)</td></tr>
<tr><td rowspan="3">Explosion residual effects (dispersion and impact of explosive particles and detonation products)</td><td>Impact of explosive particles on the environment</td></tr>
<tr><td>Impact of particles of the object’s fragmentation shell on the environment</td></tr>
<tr><td>The impact of particles of the destroyed object on the environment</td></tr>
<tr><td>Quantitative state of the civilian population</td><td colspan="3">Total quantity and ratio of urban and rural residents</td></tr>
<tr><td>Age structure of the population</td><td colspan="3">Total quantity and ratio of people of different age groups</td></tr>
<tr><td rowspan="8">Description and population of the settlement</td><td colspan="3">A farmstead (a house for 1 family, with accompanying buildings, in rural areas) — up to 25 people</td></tr>
<tr><td colspan="3">Village (small community registered in rural areas) — from 100 to 1000 people</td></tr>
<tr><td colspan="3">Urban-type settlements — from 1,000 to 10,000 people</td></tr>
<tr><td colspan="3">Small towns — up to 50 thousand people</td></tr>
<tr><td colspan="3">Average city — from 50 thousand to 250 thousand people</td></tr>
<tr><td colspan="3">Large city — from 250,000 to 500,000 people</td></tr>
<tr><td colspan="3">Large city — from 500,000 to 1 million people</td></tr>
<tr><td colspan="3">Millionaire city — more than 1 million people</td></tr>
</table>

The concepts in Table have the following meaning.

Dual-purpose structures are ground or underground structures or their separate parts that are designed or adapted for use for their main functional purpose, including for the protection of the population, and in which conditions for the temporary stay of people are created.

Quick-build civil protection structures of modular type should ensure protection of the population to be sheltered from the estimated impact of destruction means in accordance with ДБН В.2.2-5 within the normative time established in accordance with ДБН В.1.2-4.

Quick-build modular storage facilities must provide protection against:

- exposure to excessive pressure at the front of an airborne shock wave of at least 100 kPa;
- local and general effects of conventional munitions (small arms, fragments of hand grenades, artillery ammunition and aerial bombs).

External enclosing structures of prefabricated modular radiation protection shelters should provide protection of the public against:

- local and general effects of conventional munitions (small arms, fragments of hand grenades, artillery ammunition and aerial bombs);
- exposure to external ionising radiation and excessive pressure of the airborne shock wave front, depending on the location.

The simplest shelters are fortifications or basements, or other underground structures where people can temporarily stay in order to reduce the combined damage from hazards and from the effects of munitions during a special period.

To understand the destructive effect of aircraft even after they are shot down in the air, we will model this process. After an aircraft is detonated in the air, the explosion products, expanding to a value equal to 10–12 charge radii before atmospheric pressure is restored, will displace the air adjacent to them, compressing it and setting it in motion. However, the expansion process will not end there. By inertia, it will increase to a value close to 20 charge radii. At this point, the layer of compressed air is detached from the explosion products and, due to the energy it receives, continues to move independently at supersonic speed, representing the so-called air shock wave. The latter captures significant masses of air as it moves. Thus, the enlarged air moves behind the shock wave front, leaving behind a region of rarefaction where the pressure drops below atmospheric pressure.

As the energy of the shock wave moves away from the centre of the explosion, it is dispersed spherically in the environment, heating the air. Thus, the pressure amplitude (jump) gradually decreases with increasing distance from the centre of the explosion, and the velocity at the wave front decreases, becoming the speed of sound. As a result, the shock wave gradually fades away. However, the depth of the wave, namely the time of its overpressure action, increases with distance from the centre of the explosion [40].

The shock wave from an aircraft crash reaches the ground and is reflected from it and moves towards the centre of the explosion as a reflected shock wave. As it moves in the air, which is thinned and heated by the previous shock (incident) wave, its speed is greater than the speed of the incident shock wave, and at a distance approximately equal to the height of the explosion, the reflected shock wave catches up with the incident shock wave and, merging with it, forms the so-called main shock wave, which carries.

Thus, when an aircraft is shot down, the reflected wave will usually move along with the main wave with the pressure at its front close to the main wave. Therefore, there is a common assumption that the shock wave from a ground explosion of an aircraft and the shock wave from its impact within the irregular reflection zone are zones of increased pressure hypothetically created by a double mass charge. This will be true when calculating the dynamic loads of the rigid surfaces of the civilian shelter facilities. However, when calculating non-rigid surfaces, it is advisable to take into account the correction factor with the charge mass.

Coefficients are assigned to the input values, and the ASNA software determines the weight of each value through mathematical modelling. This can take into account mutual exclusions or complementarities in the Kolmogorov–Chapman system of equations on which the selected software is based.

Using the systems engineering approach, it is possible to obtain calculations for systems that do not yet exist, when reference values are not yet available. The methodology allows values to be obtained if specific values are provided, such as concrete thickness, reinforcement diameter, etc.

Based on the values given in Table, we calculated and obtained graphs (Figs. 2–5), which allow us to conclude that the results obtained are adequate to the values obtained by other scientists [41].

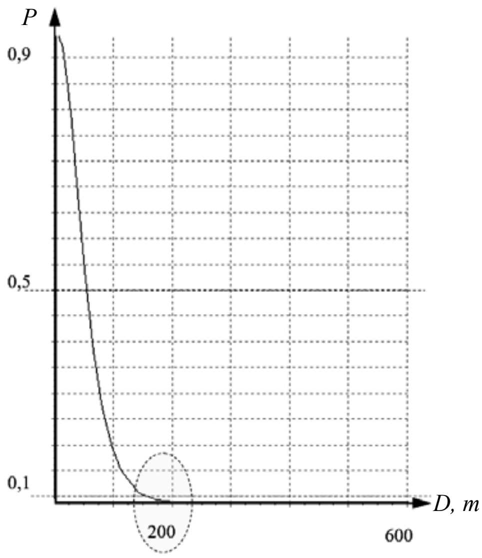

Fig. 2. Diagram of the location of the civilian shelter facilities from the residence of citizens

The analysis of Fig. 2 shows that the distance (*D*) of the location of the control centre from the dwellings should not exceed 200 m. Depending on the time of day (day, night), weather conditions (slippery road in winter, heavy rain in summer), presence of children under 6 years old in the family, elderly people over 60 years old, people with different health conditions, the time for moving increases. Therefore, the location of a civilian shelter facilities against aircraft strikes at a distance of more than 200 m reduces the likelihood of protecting people from damage of varying degrees.

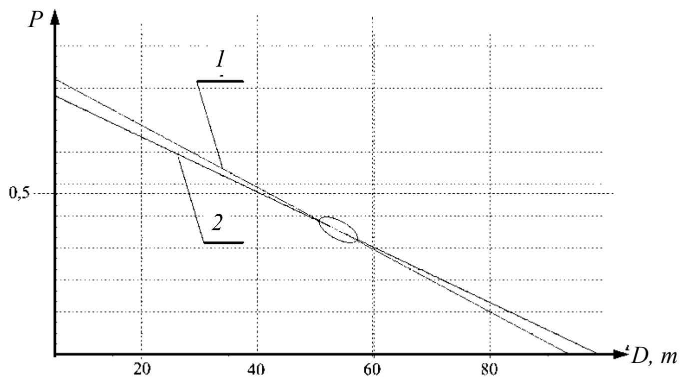

Fig. 3. Graph of the probability of damage versus wall thickness of typical civilian shelter facilities (*1*) and non-typical civilian shelter facilities (*2*)

The authors of this paper argue that structures of different types in the form of civilian shelter facilities can be combined as typical and non-typical. The analysis of Fig. 3 shows that the degree of protection of typical and atypical objects with wall thicknesses from 20 mm to 60 mm steel equivalent, depending on its ability to withstand shock waves and fragments of different fractions, has virtually the same properties of 54 mm thickness.

Analysis of Fig. 4 shows the following. Regardless of the type of shelter, during the open impact of a warhead (within 50 kg) of a Shahed UAV (Russian analogue is the "Герань-2"), the probability of sustaining damage at the level of 0.5 in the form of acubarotrauma of varying degrees or other injuries is within 34 m. In other words, the protection against direct impact of a Shahed-type kamikaze drones on Mamad-type premises without additional obstacles in the form of building walls or other structures (objects) is close to that of specially equipped premises. The placement of the civilian shelter facilities directly in the room allows to reduce the time for movement, i.e. staying in the unprotected area.

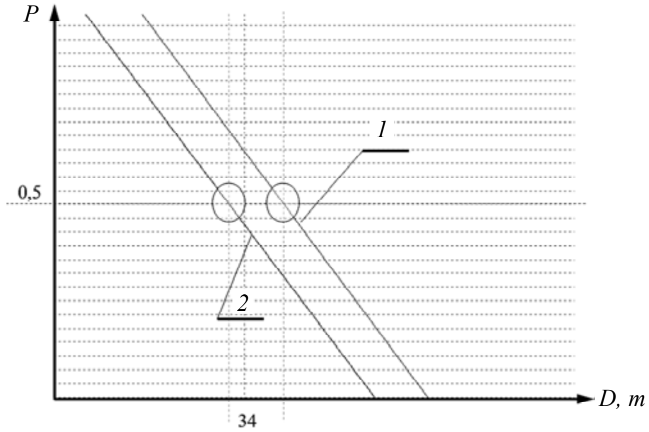

Fig. 4. Diagram of comparative characteristics of protective properties of civilian shelter facilities in the form of special rooms (*2*) and rooms of the "mamad" type (*1*)

An analysis of Fig. 5 shows that, regardless of the type of settlement, when

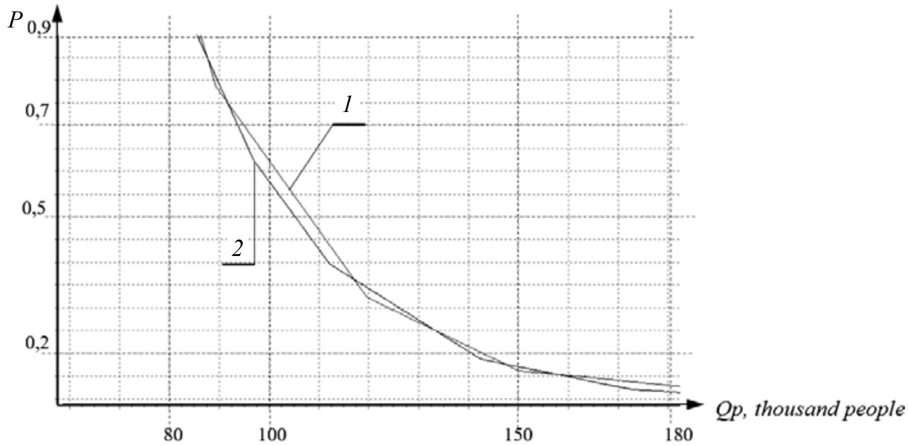

Fig. 5. Graph of the dependence of the protective properties of the civilian shelter facilities on the number of civilians in need of protection

the population is 87.000 or more, and despite the uniformity of the warning, the number of collective-type civilian shelter facilities is significantly reduced. The authors deliberately did not take into account cities with a population of more than one million people, because in these cities the communication infrastructure and the sense of danger are more developed than in much smaller towns and villages, where people's confidence in their own safety is based mainly on the principle of self-complacency. Those settlements with a population of less than 87.000 should be considered according to a different principle or be merged into certain structures. This is because it is difficult to assess the feasibility of building civilian shelter facilities for a population of up to 10.000 inhabitants without taking into account economic indicators. Private households allow for the construction of various types of structures where it would be possible to hide from enemy aircraft.

DISCUSSION OF THE RESULTS OF THE STUDY OF THE CRITERION FOR THE OPTIMAL CHOICE OF CIVILIAN SHELTER FACILITIES

This paper calculates a generalised criterion for the optimality of the selection of civilian shelter facilities in the form of regression coefficients (4). It is based on the developed model for assessing the effectiveness of the use of civilian protective equipment, the flowchart of which is shown at Fig. 1. The optimality criterion is capable of determining a generalised indicator of a linear model for selecting civilian shelter facilities during attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas.

The essence of the proposed approach is to adapt the existing mathematical apparatus to the real conditions of operational decision-making through the use of a generalised optimality criterion. The weighting criteria make it possible to determine how relevant individual facilities are in a particular situation, which will increase the efficiency of planning the selection of civilian shelter facilities during attacks by ballistic (cruise) missiles and kamikaze drones s in urbanized areas.

In order to select sheltering civilians from attacks, it is necessary to have a set of physical (technical) states of civilian shelter facilities with a set of values and signs sufficient to assess their reliability. This necessitates the creation and implementation of a new system of concepts based on a more detailed accounting of the results of civilian protection. In turn, this to some extent limits the applicability of the research results and requires preliminary data preparation for their use.

A similar study [42], which analysed the use of tunnels as civilian shelter facilities, is based on the use of hierarchy analysis. This requires users to perform a large number of pairwise comparisons and importance assessments. For large and complex problems, this can be a time-consuming and confusing process. Paper [43] uses a stepwise weighting factor analysis to develop a model for rapidly assessing the vulnerability of office buildings to explosion. However, this multi-criteria decision-making method may not be sufficiently transparent about how it arrives at the final rankings and decisions. This can be a concern in situations where stakeholders need to understand the reasoning behind decisions. The research presented in this paper does not have these shortcomings. Its peculiarity is the focus on applying the choice of the civilian shelter facilities in urbanized areas, which leads to the inclusion of a significant number of indirect indicators in the calculation.

The advantages of the proposed approach are as follows:

- versatility: the generalised optimality criterion can be applied to different types of civilian shelter facilities in the context of attacks by ballistic (cruise) missiles and kamikaze drones s in urbanized areas;

- time and resource savings: compared to traditional assessment methods, the time and resources required to assess the suitability of civilian shelter facilities against ballistic (cruise) missile and kamikaze drones attacks can be reduced;
- decision-making support: application of the generalised optimality criterion can help to make a rational decision on the informed choice of civilian shelter facilities with objective data and conclusions obtained also on the basis of mathematical models on the course of possible consequences.

The limitation of this study is that the proposed solutions address only a few types of possible causes of damage (ballistic missile, cruise missile or kamikaze drones and do not include fragmentation and high-explosive projectiles.

Some possible disadvantages may include:

- subjectivity of the choice of criteria: the choice of criteria used in the model can be subjective and dependent on the researcher, which can lead to incorrect or biased results;
- increased requirements for input data: the development and application of the model may require a significant amount of data that may be difficult to obtain or process.

Increasing the protection of the population can be achieved by creating a fund of protective structures and, on its basis, informing the population about the optimal choice of civilian shelter facilities.

A fund of civilian shelters can be created by:

- implementation of the provisions of the sections (schemes) of engineering and technical measures for civil protection of urban planning and design documentation of construction projects in terms of construction (adaptation) of protective and dual-purpose structures;
- integrated development of the underground space of cities and other settlements to accommodate social, industrial and economic facilities;
- creation and registration of existing dual-purpose structures and simple shelters, other operated facilities, including underground and above-ground buildings, mine and other workings and underground cavities;
- construction of quick-build protective structures and arrangement of the simplest shelters during the special period;
- proactive acquisition (manufacture) and maintenance in peacetime of special designs of quick-build shelters, including block-modular type, ready for installation and use.

Public awareness will be based on the data on the protective structures fund. It can take various forms: posting information on a website or physical objects, development of an application for mobile phones that will take into account a person's location and distance to nearby civilian shelter facilities, etc. This is planned to be put into practice in the course of further research and experiments.

Along with the results obtained, the authors of this paper consider it expedient to use the experience of Israel, which consists in partial abandonment of the so-called "public" shelters in the future and transition to "individual" shelters in the homes of Ukrainian citizens. First, the flight time of ballistic missiles is measured in minutes. Secondly, there is a problem of ignoring air raid warnings among the public. Thirdly, the maintenance of collective civilian shelter facilities is a rather cumbersome task even for Israel.

Thus, blindly and thoughtlessly copying the experience of other countries is a futile exercise. After all, from the mentality of the population, traditions and geographical location to the enemy, all of which impose significant limitations on someone else's experience. Therefore, it is important to evaluate and take into account the results of others, but the main thing is to create our own authentic model of protecting civilians from missile and Kamikaze drones . Moreover, such work should be carried out on an ongoing basis and not just for years, but for decades.

CONCLUSIONS

1. A generalised model for assessing the use of civilian shelter facilities selecting has been developed by applying linear forms of factor linkage in combination with a generalised optimality criterion in the form of a linear combination of local criteria.

2. The vectors of weighting coefficients of the proposed model were determined, taking into account their peculiarities in the context of attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas.

3. The method of multivariate regression analysis was chosen as a method of studying the correlation between the generalised criterion and the observed feature. Its advantages are the interpretability of the impact of individual independent variables on the dependent variable, ease of use, good handling of linear dependencies and the ability to detect changes, as well as relatively simple modelling of the influence of variables on each other.

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INFORMATION ON THE ARTICLE

Vadim V. Yakovenko, ORCID: 0000-0001-8591-6998, Odesa Military Academy, Ukraine, e-mail: yakob@ukr.net

Nataliia I. Furmanova, ORCID: 0000-0002-8670-2948, Zaporizhzhia Polytechnic National University, Ukraine, e-mail: nfurmanova@gmail.com

Ihor M. Flys, ORCID: 0000-0001-6334-0027, Hetman Petro Sahaidachnyi National Army Academy, Ukraine, e-mail: 9imf61@gmail.com

Oleksandr Yu. Malyi, ORCID: 0000-0002-8457-8154, Zaporizhzhia Polytechnic National University, Ukraine, e-mail: docsasha2@gmail.com

Oleksii Yu. Farafonov, ORCID: 0000-0001-5963-5033, Zaporizhzhia Polytechnic National University, Ukraine, e-mail: farafon@zntu.edu.ua

Harri V. Moroz, ORCID: 0000-0003-4636-4961, Zaporizhzhia Polytechnic National University, Ukraine, e-mail: garrymrz206@gmail.com

ВИЗНАЧЕННЯ УЗАГАЛЬНЕНОГО КРИТЕРІЮ ОПТИМАЛЬНОСТІ ВИБОРУ ЗАСОБІВ УКРИТТЯ ЦИВІЛЬНОГО НАСЕЛЕННЯ ВІД АТАК БАЛІСТИЧНИМИ (КРИЛАТИМИ) РАКЕТАМИ ТА УДАРНИМИ БЕЗПІЛОТНИМИ ЛІТАЛЬНИМИ АПАРАТАМИ В УРБАНІЗОВАНИХ РАЙОНАХ / В.В. Яковенко, Н.І. Фурманова, І.М. Флис, О.Ю. Малий, О.Ю. Фарафонов, Г.В. Мороз

Анатоція. Об’єктом дослідження є планування вибору засобів укриття цивільного населення від атак балістичними (крилатими) ракетами та ударними безпілотними літальними апаратами (БпЛА) в урбанізованих районах. Розроблено узагальнену модель оцінювання вибору засобів укриття цивільного населення шляхом застосування лінійних форм зв’язку факторів у поєднанні з узагальненим критерієм оптимальності у вигляді лінійної комбінації локальних критеріїв. Як метод дослідження кореляції між узагальненим критерієм та спостережною ознакою обрано метод багатовимірного регресійного аналізу. Розраховано узагальнений критерій оптимальності вибору засобів укриття цивільного населення від атак балістичними (крилатими) ракетами та ударними БпЛА в урбанізованих районах у вигляді коефіцієнтів формування регресії. Критерій здатен сприяти спрощеному визначенню узагальненого показника лінійної моделі планування захисту мирних громадян у містах поза межами бойових дій. Вихідними даними є набір фізичних (технічних) станів укриттів з переліком величин і ознак, достатніх для оцінювання їх стійкості до високих динамічних навантажень.

Ключові слова: критерій оптимальності, засоби укриття цивільного населення, ваговий коефіцієнт, ракетні атаки.