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EVALUATING THE RISKS TO UKRAINE'S INFRASTRUCTURE IN A WARTIME CONTEXT

This study explores the assessment of risks for infrastructure objects in war conditions on Ukraine's territory. The article focuses on the main trends and changes in the damage to Ukrainian infrastructure caused by Russian military aggression, both at the regional and national levels. It includes an assessment of the risks of damage to infrastructure from artillery and missile attacks across various administrative regions of Ukraine. The regions were ranked based on the risk level associated with infrastructure losses in wartime conditions. The analysis utilized available statistical data to perform the risk assessment, adapting a model commonly used in EU countries. A risk matrix was developed to quantify direct infrastructure losses from artillery and missile attacks throughout the conflict. The matrix encompasses 16 different types of infrastructure facilities. Evaluations indicate a heightened risk for assets in industry, agriculture, education, and energy sectors. Meanwhile, assets related to the forest fund, trade, housing and communal services, culture, tourism, sports, healthcare, and transport face average risk. Other infrastructure types examined in this study, including administrative buildings, digital infrastructure, social services, and the financial sector, are classified as having a low risk of loss. The analysis of the risk of direct infrastructure losses from artillery and missile attacks over the year revealed that residential buildings and critical infrastructure are particularly vulnerable. The calculations indicated that two types of infrastructure are at exceptionally high risk for direct losses due to these attacks. The results show that direct damage to infrastructure objects from shelling during military operations can increase by more than two orders of magnitude compared to damage from emergencies of various origins in peacetime. The authors propose a methodology to assess the risks of damage to infrastructure from artillery and missile attacks at the level of administrative regions of Ukraine and to adapt the data to evaluate the risk of infrastructure objects according to the model used in EU countries.

Key words: *risk, infrastructure, evaluation, wartime, environment, risk assessment, natural environment, contamination.*

Formulation of the problem. The Russian military aggression against Ukraine has not only caused widespread destruction of residential and critical infrastructure but has also severely disrupted the normal operations of numerous enterprises. This has resulted in an unprecedented decline in the quality of essential resources and a catastrophic ecological imbalance in the country's natural environment. Across various regions of Ukraine, the challenges associated with waste management, hazardous chemical substances, and environmental preservation are worsening, leading to excessive pollution of soil and water resources and the disruption of landscapes and nature conservation areas.

The destruction of sewage and water treatment systems has caused a significant increase in toxic substances such as zinc, copper, chromium, lead, cadmium, and others in natural water bodies. This contamination has made providing quality water to certain regions' populations impossible. Additionally,

complications have arisen in the operation of nuclear energy facilities in Ukraine, including the Zaporizhzhya nuclear power plant, due to damage and disruptions to critical energy infrastructure. These factors contribute to an increased threat to environmental safety, which includes cross-border implications.

The extensive destruction and deterioration of vital environmental components caused by the war necessitate a significant reevaluation of the existing methodology in Ukraine for assessing the ecological damage resulting from military operations. Since the beginning of the conflict, the destruction of residential and communal infrastructure has occurred due to both direct hostilities and targeted missile and artillery strikes aimed at critical facilities essential for civilian life.

Analysis of recent research and publications. As a result of shelling and active combat, some cities have experienced destruction exceeding 80%. Preliminary estimates suggest that failing infrastructure facilities cost at least $110 billion. The estimated damage to housing alone amounts to over 50 million square meters. The impact extends to educational and healthcare institutions, housing and communal enterprises, administrative buildings, bridges, crossings, and transport infrastructure.

According to the "Russia Will Pay" project, the total direct damage from the destruction of housing and infrastructure in just six months of full-scale war amounts to $108.3 billion, or 2.9 trillion hryvnias. During this period, at least 129,900 residential buildings were damaged, resulting in losses of $47.7 billion. Notably, 38% of these buildings were destroyed beyond possible restoration. The damage to the housing stock is unevenly distributed among regions, with the Donetsk, Luhansk, Kharkiv, and Kyiv regions collectively accounting for over 82% of the total damage in Ukraine. In addition, the infrastructure sector incurred losses of $31.6 billion, destroying 2,217 educational institutions, 903 medical facilities, and 89 social institutions.

The recording and assessment of the destruction and the direct damage caused by it are ongoing. However, the indicators obtained can only be considered preliminary and are subject to continuous updates and revisions, typically reflecting increased estimates. Additionally, the experience of partially restoring residential infrastructure in the recently liberated territories highlights the importance of including estimates for total damage costs. This should account for expenses related to the dismantling and disposal of debris and the loss of essential equipment, particularly that of water treatment facilities, heating points, and the vehicle fleet for housing and communal services.

Adopting the approach proposed by the World Bank to assess restoration costs effectively is advisable. This approach combines losses from destruction, defined as the cost of constructing new residential, social, and infrastructure facilities on the sites of the destroyed ones, with economic losses stemming from the broader impact of hostilities – these indirect losses may even surpass direct losses. Current assessments rely on directly recording and analysing reports from authorities, local governments, the media, and citizens about the damage, thus providing only a descriptive evaluation of losses.

Current data from the World Bank highlights the significant economic losses from military actions affecting various infrastructure facilities in Ukraine [1]. Research into emerging trends and the nature of threats – military and otherwise – globally indicates that the risk of such occurrences is rising [2]. This analysis reviews critical approaches to assessing risks from different threats to infrastructure in Ukraine [3, 4] and around the world [5–7]. The findings reveal a substantial increase in threats and a decrease in the security levels of many critical infrastructure objects in Ukraine, primarily due to artillery and missile attacks by Russian forces. These attacks have caused widespread destruction and disrupted the operation of various infrastructure types [8, 9]. Moreover, the analysis of relevant publications points out that the destruction and damage to critical infrastructure, including energy companies, water treatment facilities, chemical plants, and agricultural enterprises, pose a severe threat to the population's and the environment's safety.

Research in the field of prevention and countermeasures against various threats indicates that protecting the population and the environment from natural, man-made, and military hazards requires a risk-oriented approach. This approach is essential for effectively preventing and reducing the risk of dangerous incidents at infrastructure facilities [10, 11]. Additionally, it is necessary to recognize that the intensification of ecological and man-made threats, exacerbated by war, leads to significant issues such as the pollution of river basins and groundwater and the destruction of landscapes and protected natural areas. These factors greatly diminish the population's safety in regions experiencing active military operations in Ukraine.

In today's world, there are increased physical risks stemming from military aggression, natural disasters, and climate change. These factors contribute to a rise

in the frequency and intensity of extreme weather events and lead to long-term shifts in average climate conditions. If adequate precautions are not taken, this can diminish the capacity and effectiveness of certain types of infrastructure. Furthermore, there is some uncertainty surrounding the identification of critical infrastructure since the relevant sectors and categories of entities are not consistently recognized as essential across all EU member states [12, 13].

Actions taken by EU member states to identify and enhance the resilience of critical entities should follow a risk-based approach that priorities those entities best suited to perform essential social functions or economic activities. Each Member State must assess relevant natural and anthropogenic risks within an agreed framework to ensure this targeted strategy. This assessment should consider cross-sectoral and cross-border risks that could impact the delivery of essential services. These risks may include accidents, natural disasters, security emergencies, health crises such as pandemics, hybrid threats, and other antagonistic threats like terrorism, criminal infiltration, and sabotage.

In the year since the beginning of the full-scale Russian military invasion, the total amount of direct documented damage to residential and non-residential real estate and other infrastructure amounted to more than $143.8 billion in replacement value. Since the beginning of the full-scale invasion on February 24, 2022, Russia has fired almost 5,000 missiles on the territory of Ukraine [14].

In the first weeks of the war, from the end of February to the beginning of March, combat operations were conducted on the territory of 10 regions. As of this time of year, hostilities continue in the Kharkiv, Luhansk, Donetsk, Kherson, and Zaporizhia regions. The most affected in terms of direct losses of infrastructure are the administrative areas of Ukraine in which hostilities were directly conducted: Donetsk, Kharkiv, Luhansk, Mykolaiv, Zaporizhzhya, Kyiv, and Chernihiv regions Fig. 1 [9].

Among the cities that suffered the most during the war, such as Maryinka, Mariupol, Irpin, Kharkiv, Chernihiv, Severodonetsk, Lysychansk, Vugledar, Sumy, Rubizhne, Izyum, Mykolaiv, Bakhmut, and Volnovakha can be singled out. The continuation of the aggression of the Russian Federation throughout 2022 and at the beginning of 2023 led to an increase in the amount of damage caused both by missile strikes on the country's infrastructure, especially in the energy sector, and by shelling of cities and towns, active military operations in the south and east of Ukraine.

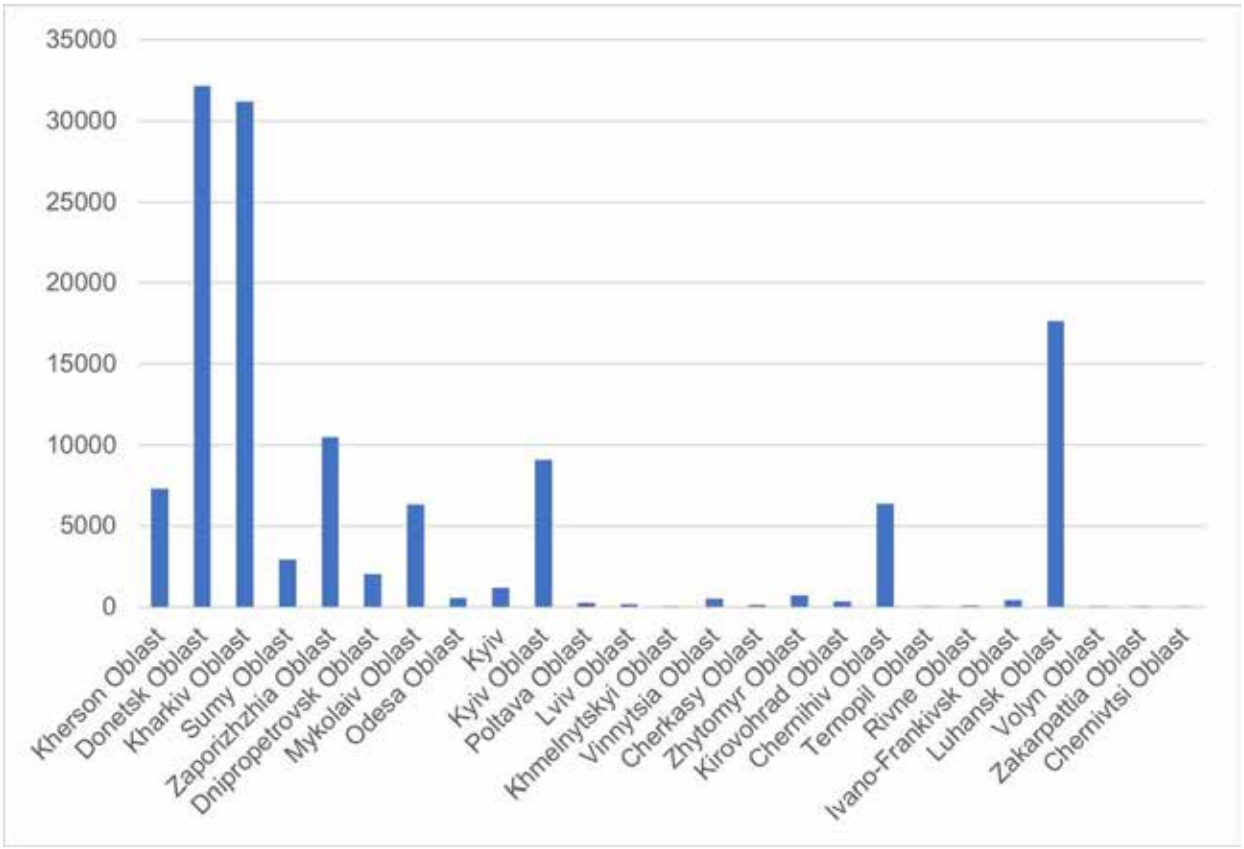

Fig. 1. Direct losses of the infrastructure of Ukraine from February 2022 to March 2023, million dollars [9]

Task statement. The purpose of the article is to analyze the regional characteristics of losses of infrastructure objects from war, to assess the risks of damage to infrastructure from artillery and missile attacks at the level of administrative regions of Ukraine, to adapt the available data and to assess the risk of direct losses of infrastructure from artillery and missile attacks during the year of the war for various types of infrastructure facilities.

The research tasks are to assess the risks of damage to infrastructure from artillery and missile attacks at the level of administrative regions of Ukraine, adapt data and use them to evaluate the risk of infrastructure objects according to the model used in EU countries, build an appropriate risk matrix of infrastructure losses from artillery and missile attacks, and assess its level.

The choice of research methodology is primarily due to the need to overcome the uncertainty that arises during decision-making on protecting critical infrastructure objects in war conditions. It is also related to Ukraine's foreign policy course towards European integration and the need to introduce and adapt modern approaches to risk assessment used in the EU to domestic conditions. In addition, it is necessary to consider the difficulty of obtaining the required data on critical infrastructure objects to conduct such an assessment in military operations.

Outline of the main material of the study. The article considers critical infrastructure as an asset, object, equipment, network, or system or a part of an asset, object, equipment, network, or system necessary to provide essential services [15]. Critical service means a service that is critical to the maintenance of vital societal functions, economic activity, public health and safety, or the environment.

Risk is considered in the article as the possibility of loss or disruption caused by an incident, which can be expressed as a combination of the magnitude of such loss or disruption and the likelihood of the occurrence. An incident is considered an event that can potentially disrupt or significantly disrupt the provision of critical services. It is evident that in war conditions, missile and artillery attacks, which cause the most significant losses to infrastructure objects, are considered incidents.

Risk assessment at work is considered a general process of determining the nature and extent of risk by identifying and analyzing the potentially relevant threats, vulnerabilities, and hazards that could lead to an incident and assessing the potential loss or failure of critical service caused by this incident.

In general, risk assessment includes several stages:

- identification of risks as a process of their recognition and description;
- risk analysis, which involves understanding the nature of the risk and determining its level;
- risk assessment involves comparing risk analysis results with criteria to determine whether the risk is acceptable or permissible.

Suppose the task of prevention and preparedness for a specific type of threat is solved. In that case, the risk can be quantified as a function of the likelihood of the occurrence of the danger, exposure (the total cost of all elements exposed to risk), and vulnerability (the specific effect of the exposure) [6]. At the same time, the risk of loss and damage to infrastructure facilities in the event of incidents during the year can be determined according to [16] as:

$$R_T = \sum_{i=1}^{n} P_{Ti}\left(V_{T1i}\cdot L_{T1i}\cdot N_{T1i} + V_{T1i}\cdot L_{T2i}\cdot N_{T2i}\right) = \\ = \sum_{i=1}^{n} P_{Ti}\left(\frac{N_{T1i}}{N_{Ti}}\cdot L_{T1i}\cdot N_{T1i} + \frac{N_{T2i}}{N_{Ti}}\cdot L_{T2i}\cdot N_{T2i}\right), \quad (1)$$

Where PTi is the likelihood of the i-th incident with losses for the infrastructure facilities of the particular region; VT1i – is the vulnerability of infrastructure objects to destruction from the i-th incident; VT2i – the vulnerability of infrastructure objects to damage from the i-th incident; NT1i – the number of destroyed infrastructure facilities during the i-th incident; NT2i – the number of damaged infrastructure objects as a result of the i-th incident; NTi – the total number of infrastructure facilities in this region; LT1i – loses from the destruction of infrastructure facilities; LT2i – loses from damage to infrastructure facilities as a result of the i-th incident.

At the same time, in EU countries, it is recommended to use a 5 x 5 risk matrix to visualise the assessment results when conducting a national risk assessment for critical infrastructure (Fig. 2) [6].

Risk assessment should be based on three impact categories: adverse consequences for people (population), economy (and environment), and political and social consequences. For the first two impact categories, the negative consequences are quantified as the number of dead (injured) persons or economic losses in UAH (Euro). Implications for the third category of influence, regarding social and political interrelationships, are determined through qualitative indicators.

In the European Union, each country must carry out a risk assessment for each category of consequences and accordingly build three different risk matrices when carrying out a risk assessment for

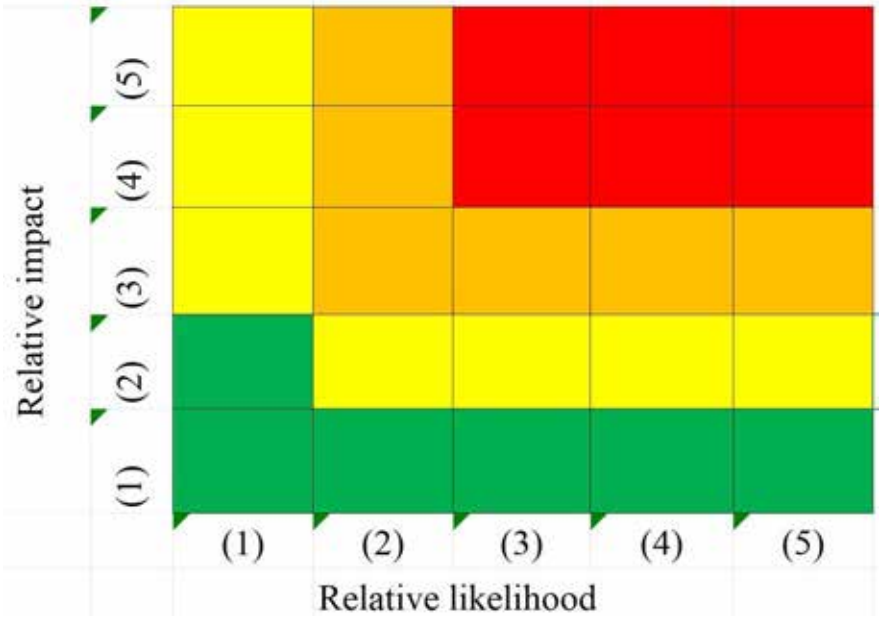

Fig. 2. Example of risk matrix (green – low level, yellow – average level, orange – above average level, red – high level)

critical infrastructure. Among all threats of various origins to the security of critical infrastructure, the following are identified as the most important [5]:

- natural: floods, extreme weather events, forest fires, earthquakes, epidemics and pandemics, epizootics;
- technogenic: a) non-malicious: industrial accidents, nuclear/radiological accidents, transport accidents, loss of critical infrastructure; b) malicious: cyber-attacks, terrorist attacks.

In this work, the risk of direct infrastructure losses from missile and artillery strikes at the regional level was assessed according to the data of the Kyiv School of Economics and the Ukrainian Helsinki Human Rights Association regarding the losses of various types of infrastructure and the volume of missile and artillery shelling in the regions of Ukraine [9, 14].

At the same time, the likelihood of occurrence of dangerous situations and the possibility of losses from them are calculated based on the specified statistical data. On this basis, the corresponding risk of infrastructure losses from missile and artillery strikes is determined, which was done to solve the purpose of this publication (Fig. 2). The likelihood of artillery and missile strikes was defined as the ratio of the number of attacks in the corresponding region of the country to their total number in Ukraine, which occurred during the year of the war (Fig. 3).

The results of the calculations indicate that the highest likelihood of artillery and missile attacks is observed in the Donetsk, Zaporizhzhia, Kharkiv, Kherson, Chernihiv, and Luhansk regions.

Considering the obtained results of the assessment of the likelihood of artillery and missile attacks, the risk of direct infrastructure losses from missile and artillery attacks was further assessed, missile attacks, exposure, and the corresponding impact in the form of economic losses (Fig. 4).

The assessment results show that for almost all regions of the country, there is a risk of damage to the infrastructure by Russian shelling. At the same time, the highest level of risk of infrastructure losses from missile and artillery fire in the regions of Ukraine is noted in the Kharkiv and Donetsk regions. A high level of risk is characteristic of the Zaporizhia, Luhansk, Kherson, Chernihiv, and Mykolaiv regions. The average level of risk of infrastructure losses from rocket and artillery fire is noted for the Kyiv, Dnipropetrovsk, Sumy, Odesa, and Zhytomyr regions. The low level of risk mainly refers to the Cherkasy, Poltava, Vinnytsia, Lviv, Ivano-Frankivsk, and Khmelnytsky regions.

An analysis of the data on direct losses by infrastructure type shows that the most significant increase is due to the increase in losses of the housing stock. Thus, this amount increased to $53.6 billion over the past three months in February 2023 [9].

At the same time, it should be noted that the three most affected areas, in addition to the destruction of the housing sector, include the infrastructure area, with losses amounting to $36.2 billion, and industry

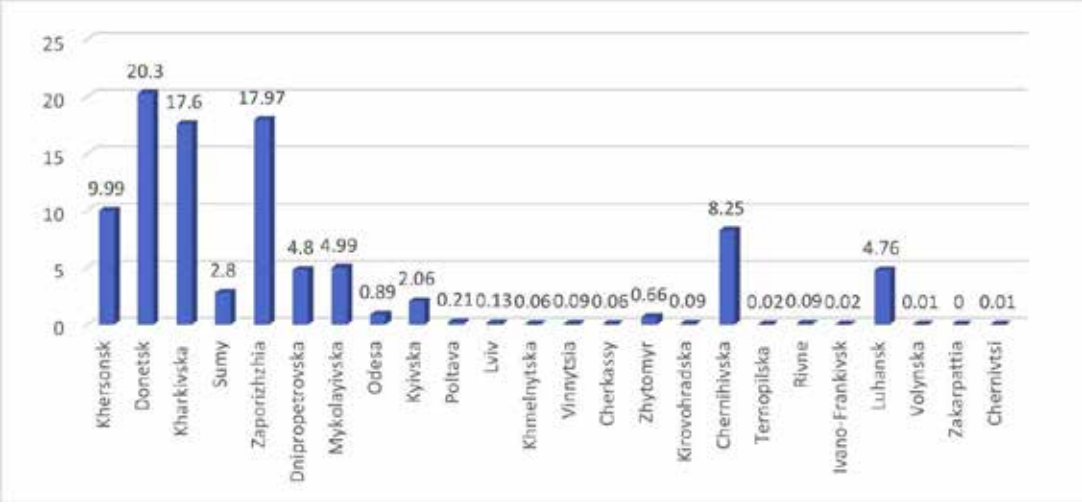

Fig. 3. Likelihood of artillery and missile strikes in the regions of Ukraine, %

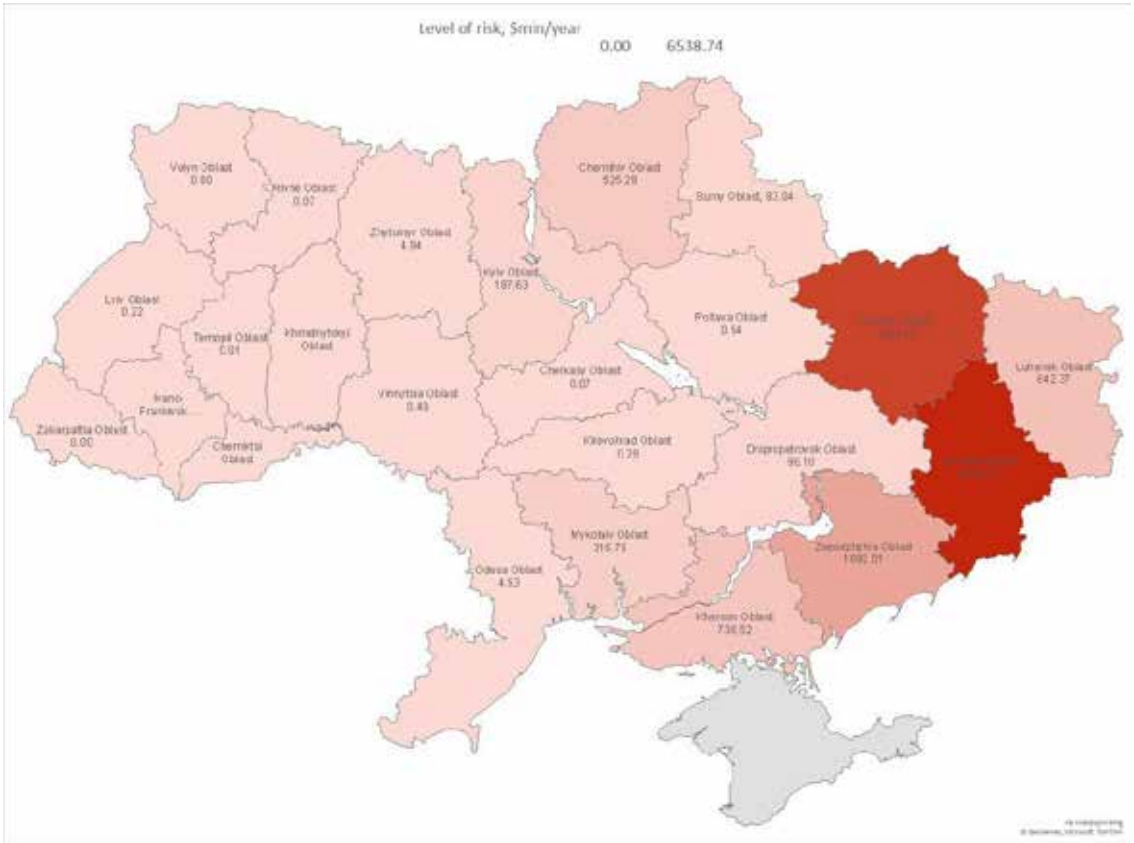

Fig. 4. The risk of infrastructure losses from missile and artillery fire in the regions of Ukraine

and damaged enterprises – for $11.3 billion. Another $8.9 billion was destroyed and damaged by Russian educational institutions in which Ukrainians, pupils, and students from other countries studied. Damages caused to land resources and agriculture during the active phase of armed aggression from February 24, 2022, are estimated at $8.7 billion.

Compared to the beginning of June 2022, there was a significant increase in the number of destroyed and damaged infrastructure objects: from 121,000 to 153,000 objects, the number of residential objects affected by the war increased from 777 to 1,216 – medical facilities, from 111 to 630 – administrative buildings, from 105.2 thousand to 207.5 thousand – private cars.

The tactics of massive missile and drone attacks on Ukrainian energy facilities, which Russia began to use in October 2022, led to the fact that direct losses

in the energy sector are already estimated at $8.1 billion, the central part of which fell on the electric power industry.

The risk of infrastructure losses by category is assessed according to the Kyiv School of Economics data regarding the formation of direct losses for various infrastructure objects. Thus, a risk matrix is constructed. At the same time, the likelihood of dangerous events and the possibility of economic losses from them are calculated based on statistical data. On this basis, the corresponding dependence is formed, which was done to solve the purpose of this publication (Fig. 3). The likelihood of the occurrence of dangerous events (missile and artillery strikes) was determined as the ratio of the number of such events for the corresponding type to their total number that occurred during the period from February 2022 to March 2023 (Table 1).

The assessment results indicate that residential buildings, infrastructure facilities, the energy industry, and the agricultural sector are characterized by the greatest likelihood of infrastructure losses in Ukraine. At the same time, residential buildings, infrastructure facilities, enterprise assets, and industry are characterized by the highest likelihood of shelling.

Considering the results obtained in assessing the likelihood of missile and artillery attacks and losses of various types of infrastructure, the EU model constructed a risk matrix (Fig. 5).

It is important to note that residential buildings and critical infrastructure facilities typically face a high risk of direct losses. Enterprises in sectors such as industry, agriculture, education, and energy also have an increased level of risk. In contrast, assets related to the forest fund, trade, housing and communal services, culture, tourism, sports, health care, and transport are considered to have an average level of risk.

Other types of infrastructure objects considered in this study, including administrative buildings, digital infrastructure objects, the social sphere, and the financial sector, are characterized by low risk.

In management decisions aimed at reducing losses from various types of shelling, it is crucial to focus primarily on preventing and lessening risks to residential buildings and critical infrastructure.

In war conditions, conducting risk assessments for critical infrastructure requires modern statistical data analysis methods, probability theory, and risk analysis to validate the confidence of the obtained research results.

In the context of military operations and the complex interrelationships among critical factors that contribute to threats to infrastructure, an effective risk reduction process will require the simultaneous implementation of multiple strategies. These strategies may include enhancing the protection of infrastructure and duplicating essential functions to ensure their continuity.

In the context of Russian military aggression against Ukraine, there is a growing threat of decreasing security levels, which hampers the operation of many critical infrastructure facilities. This situation arises from missile and artillery attacks, leading to severe risks of destruction and damage. An analysis of the main trends and changes

Table 1

Risk assessment of infrastructure losses by category

№	Type of infrastructure	Likelihood of losses	Likelihood of shelling	Risk category
1	Residential buildings	0.373	0.254	5
2	Critical infrastructure	0.252	0.371	5
3	Enterprise assets, industry	0.079	0.062	4
4	Education	0.062	0.076	4
5	Agrarian-industrial complex and land resources	0.061	0.059	4
6	Energy	0.056	0.061	4
7	Forest fund	0.031	0.032	3
8	Vehicles	0.022	0.017	3
9	Trade	0.018	0.022	3
10	Utilities	0.01	0.01	2
11	Culture, tourism, sports	0.015	0.012	2
12	Health care	0.012	0.015	2
13	Administrative buildings	0.004	0.004	1
14	Digital infrastructure	0.004	0.004	1
15	Social sphere	0.001	0.001	1
16	Financial sector	0.0001	0.0001	1

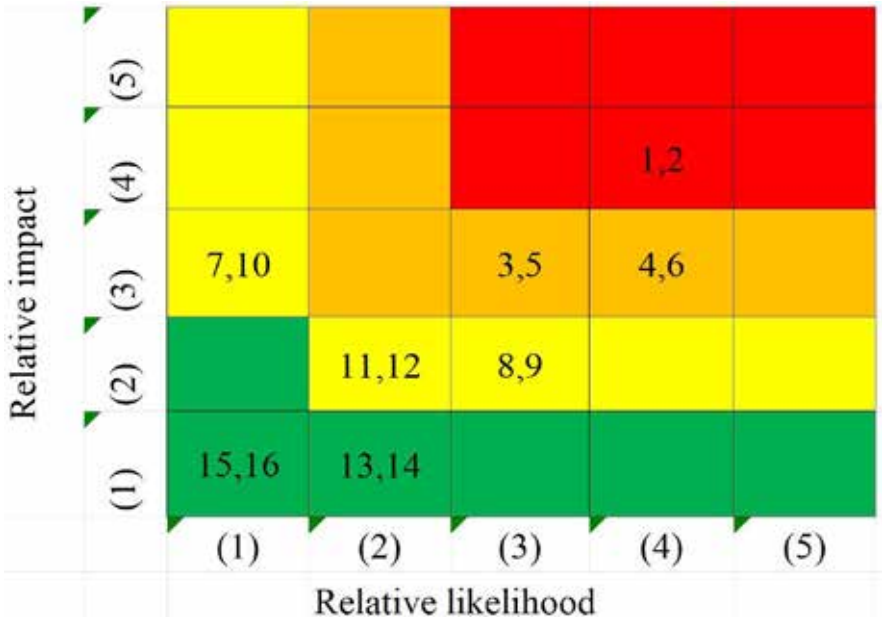

Fig. 5. Risk matrix of direct infrastructure losses from artillery and missile strikes during the year of the war: 1 – Residential buildings; 2 – Critical infrastructure; 3 – Enterprise assets, industry; 4 – Education; 5 – Agrarian-industrial complex and land resources; 6 – Energy; 7 – Forest fund; 8 – Vehicles; 9 – Trade; 10 – Utilities; 11 – Culture, tourism, sports; 12 – Health care; 13 – Administrative buildings; 14 – Digital infrastructure; 15 – Social sphere; 16 – Financial sector

in infrastructure losses across Ukraine during the war–at both regional and national levels–reveals a significant vulnerability of these facilities to missile and artillery strikes. Infrastructure in regions of Ukraine that border the Russian Federation and are in areas of active military operations are particularly affected.

Conclusions. The findings indicate that assessing risks for infrastructure in wartime should differ from evaluations made during peacetime. Data reveals that during military operations, the likelihood of damage and destruction to infrastructure significantly increases, mainly due to rocket and artillery fire. Furthermore, the direct damage to infrastructure from shelling during military operations can be more than 100 times greater than the damage caused by various emergencies in peacetime.

The assessment of the risks to infrastructure from artillery and missile attacks across Ukraine's administrative regions indicates that nearly all areas of the country face a threat from Russian attacks. The highest risk of infrastructure damage from missile and artillery fire is observed in the Kharkiv and Donetsk regions. Additionally, the Zaporizhia, Luhansk, Kherson, Chernihiv, and areas of Mykolaiv also exhibit a significant risk to various types of infrastructure.

The analysis of the risk of direct infrastructure losses from artillery and missile attacks over the year revealed that residential buildings and critical infrastructure are particularly vulnerable. Evaluations indicate a heightened risk for assets in industry, agriculture, education, and energy sectors. Meanwhile, assets related to the forest fund, trade, housing and communal services, culture, tourism, sports, healthcare, and transport face average risk. Other infrastructure types examined in this study, including administrative buildings, digital infrastructure, social services, and the financial sector, are classified as having a low risk of loss.

Future exploration in this area primarily hinges on a comprehensive assessment of the damages sustained by infrastructure due to the war. This assessment will facilitate a risk evaluation of various types of Ukrainian infrastructure at regional and national levels. It will also involve categorizing these infrastructures by type and level of risk and developing appropriate measures to mitigate potential threats that could result in significant negative impacts on critical infrastructure facilities.

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Іванюта С.П., Іваненко О.І., Плашихін С.В., Абрамова А.О. ОЦІНКА РИЗИКУ ДЛЯ ІНФРАСТРУКТУРИ УКРАЇНИ В КОНТЕКСТІ ВОЄННОГО ЧАСУ

Досліджено оцінку ризиків для об'єктів інфраструктури в умовах війни на території України. У статті розглядаються основні тенденції та зміни шкоди українській інфраструктурі, завданої російською військовою агресією, як на регіональному, так і на національному рівнях. Він включає оцінку ризиків ураження інфраструктури від артилерійських і ракетних обстрілів у різних адміністративних областях України. Регіони ранжовано за рівнем ризику, пов'язаного з втратою інфраструктури в умовах воєнного часу. Аналіз використовував доступні статистичні дані для проведення оцінки ризику, адаптувавши модель, яка зазвичай використовується в країнах ЄС. Було розроблено матрицю ризиків для кількісного визначення прямих втрат інфраструктури від артилерійських і ракетних атак протягом усього конфлікту. Матриця охоплює 16 різних типів інфраструктурних об'єктів. Оцінки вказують на підвищений ризик для активів у промисловості, сільському господарстві, освіті та енергетиці. Водночас середньому ризику піддаються активи лісового фонду, торгівлі, житлово-комунального господарства, культури, туризму, спорту, охорони здоров'я, транспорту. Інші типи інфраструктури, розглянуті в цьому дослідженні, включаючи адміністративні будівлі, цифрову інфраструктуру, соціальні послуги та фінансовий сектор, класифікуються як такі, що мають низький ризик втрат. Аналіз ризику прямих втрат інфраструктури від артилерійських і ракетних обстрілів протягом року показав, що особливо вразливими є житлові будинки та критична інфраструктура. Розрахунки показали, що два типи інфраструктури мають надзвичайно високий ризик прямих втрат

через ці атаки. Результати показують, що прямі збитки об'єктів інфраструктури від обстрілів під час військових дій можуть зрости більш ніж на два порядки порівняно зі збитками від надзвичайних ситуацій різного походження в мирний час. Авторами запропоновано методику оцінки ризиків ураження інфраструктури від артилерійсько-ракетних обстрілів на рівні адміністративних областей України та адаптації даних для оцінки ризиків об'єктів інфраструктури за моделлю, яка використовується в країнах ЄС.

Ключові слова: *ризик, інфраструктура, оцінка, воєнний час, довкілля, оцінка ризику, природне середовище, забруднення.*