Modeling and prediction of the gas pipelines reliability indicators in the context of energy security of Ukraine

Halyna Zelinska[1[0000-0003-2175-4883]], Irina Fedorovych[1[0000-0002-7139-6327]], Uliana Andrusiv[1[0000-0003-1793-0936]], Oksana Chernova[1[0000-0002-6424-7569]] and Halyna Kupalova[2[0000-0003-4486-8349]]

[1] Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska Str., Ivano-Frankivsk, 76019, Ukraine
[2] Taras Shevchenko National University of Kyiv, 60 Volodymyrska Str., Kyiv, 01033, Ukraine
zelinska_haluna@i.ua

Abstract. Many years of experience in operation of the gas transportation system shows that the largest accidents with severe consequences arise due to untimely detection and elimination of gas leaks in underground gas pipelines. The decrease in the reliability of the gas transportation system functioning can be considered from the following two perspectives: the first perspective is the economic one – it leads to an increase in the economic expenses of an enterprise; and the second perspective is the social and environmental one – it results in emergence of a threat to public health, as well as loss of human and natural resources. Hence, the issue of modeling and prediction of the reliability indicators of natural gas transportation via gas pipelines becomes especially urgent because of the requirements for reliable operation of the system. It has been proven that the main problem leading to a decrease in the reliability of the gas transportation process is the significant deterioration of fixed assets, which requires investment of considerable financial resources in the gas transportation system of Ukraine (GTS). The article substantiates that it is possible to increase the reliability of operation of the line section of the main gas pipelines (LSMGP) through a high-quality system of repairs and equipment modernization. The main factor allowing to reduce the number of accidents is considered to be timely detection of damages on gas pipelines and their prediction. It has been determined that the failure rate depends on the diameter and number of lines of a gas pipeline. The authors propose to conduct a comprehensive diagnosis of the process of reliability of gas pipelines together with of their technical and economic indicators, based on the development of a system of measures to improve the safety of gas pipelines in Ukraine. A system of measures has been developed to improve the reliability of gas pipelines operation in Ukraine.

Keywords: reliability, expenses, modeling, accidents, economic benefits, failures, prediction, safety.

1 Introduction

The most important task of Ukraine's energy security system is to provide the reliability of the inner gas transmission system. To maintain its elements and prevent their premature deterioration is technically difficult and expensive. The core reasons of the significant repair expenses in the gas pipeline system and their sharp increase at last years are: (1) increasing the average operating age of the gas transmission lines, (2) the construction of a large number of them in areas with high soil aggressiveness, high wetlands. That's why these expanses require the deeper economic justification to reduce financial costs and obtain economic benefits. These circumstances underline the great relevance and importance of the study of the economic problems of the gas transmission lines repairing. These circumstances emphasize the great relevance and importance of studying not only the technical aspect of the problem, but also the economic problems associated with the maintenance of main gas pipelines. Lack of financial resources of an enterprise leads to the search for alternative problem solutions. One of such options consists in modeling and prediction of the gas pipelines operation reliability indicators.

2 Literature review

The increase in the level of dependence of the socio-economic development on supply of energy resources shows a clear need for improvement of the scientific foundations of the country's energy security. This issue is relatively new, so many scientists and practitioners pay more and more attention to the study of the issues associated with prediction of the gas pipelines reliability indicators in the context of the country's energy security [22]. Victoria Dergachova and Nadiia Pysar [7] are proposed differential equations that take into account price factors for the fuel and energy resources, exports, imports, as well as the mutual influence of the production volumes of certain types of energy resources on others. The reliability of supply of energy resources has become one of the most urgent political issues for the countries of Central and Eastern Europe in recent years [5]. At the same time, Mabroor Hassan, Manzoor Khan Afridi and Muhammad Irfan Khan [10] pay attention to the relationship of the policy of reliable energy supply with environmental safety and sustainable development. Shahrouz Abolhosseini, Almas Heshmati and Masoomeh Rashidghalam [1] argue in their work that energy security is the dominant factor in international stability. The researchers have established that Iran and the Caucasus are reliable energy suppliers for Europe. Hence, the scientists have proposed some alternative solutions on how to compete with competing countries in order to improve energy security. Jack D. Sharples [24] concludes in the study that the absence of market mechanisms affects negatively the country's energy security and argues that Ukraine's integration into the European gas market and reduction of the bilateral Russian-Ukrainian dependence neutralizes all concerns about regional energy security in Eastern Europe. Ganna Kharlamova and Andriy Stavytskyy prove in the [14] that the energy security of Ukraine is unsatisfactory and, using the statistical analysis, carry out a detailed analysis of the natural gas supply to Ukraine. The predictions for the country's production, import, and transit of gas for 2018-2025 are calculated based on economic and mathematical approaches. The scientists conclude that the government should carefully and transparently approach the negotiation processes with other countries interested in joint projects in gas production and transportation. Also the methodology for assessing the reliability of gas supply to the natural gas pipeline system was developed and three aspects of uncertainty and the hydraulic characteristics of the natural gas pipeline system was considered [27]. In the article [8], P. Eser, N. Chokani and R. Abhari found that a projected reduction in domestic European gas production would lead to a 12% deficit in EU gas demand by 2030. And they offered two different strategies to overcome the shortage: (1) to increase liquefied natural gas imports from various global sources against increasing supply of the Russian gas pipeline through the Nord Stream, (2) a new model of the gas system that is capturing the market as well. The potentials of studying the effect of failures and recovery coefficients on integral reliability of gas distribution systems are also considered by Nikolay I. Ilkevich, Tatyana V. Dzyubina and Zhanna V. Kalinina [12].

Luo Zheng-shan, Xi Yi-chen and Wang Hong-chao [16] have developed a comprehensive assessment of the risks of gas pipelines operation, which makes it possible to predict accidents on gas pipelines and their possible consequences. Z. Y. Han and W. G. Weng [9], in their turn, proposed a complex method for quantitative risk analysis for the gas transportation system, which consists of the incident probability assessment, consequence analysis, and risk assessment.

L. Manian and A. Hodgdon [17] assessed the integrity of gas pipelines and their management, where they proved that the result of their functioning depends on efficient management. O. Ivanov, O. Avdeuk, K. Bushmeleva, I. Ivanov and S. Uvaysov [13] develop a model for calculating the reliability of the wireless sensor telecommunication system for monitoring the state of the gas transmission network, which allows to fulfill the required level of probability of no-failure operation when a certain number of the wireless sensor modules fail. In [4] discusses the elements and structure of the distributed wireless monitoring system for detecting gas leaks in real time that ensures safe and reliable operation of different objects in the gas transmission network. Chiara Belvederesi, Megan S. Thompson and Petr E. Komers [3] carry out a comparative analysis of the safety of the US and Canadian pipelines and determine that the Pipeline and Hazardous Materials Safety Administration (PHMSA) governs 76% of pipelines in the United States, while NEB controls only 9% of pipelines in Canada and offers Canadian federal agencies to improve the accuracy and consistency in the recording of past accidents and collection of pipeline data in order to prevent and minimize future pipeline failures. Nadiia Shmygol, Władysława Łuczka, Olena Trokhymets, Dariusz Pawliszczy and Ruslan Zavgorodniy [25] improved the model for diagnosing the efficiency of resources use in the Ukrainian economy gas sector on the basis of the additive-and-multiplicative multiplier, which, unlike the existing one, takes into account their changes when determining the weighting coefficients. Mykhaylo Voynarenko, Mariia V. Dykha, Oksana Mykoliuk, Ludmyla Yemchuk and Anastasiia Danilkova [26] proposed a mathematical model of the hierarchy of factors from the point of view of their influence on the energy security of an enterprise using the graph theory. The developed model of the hierarchy of factors, which is based on the applied scientific-and-methodological approach to determining their impact on the energy security of an enterprise, makes it possible to obtain a detailed understanding of the interaction of factors, as well as the relationships and impact on the energy security of an enterprise, which ultimately leads to development of complex optimal/coordinated management solutions in the context of development and implementation of an enterprise energy security system. Ensuring the reliability of the gas pipeline system, it is necessary to find the optimal distribution of funds aimed at modernization and repair of equipment, say the authors [20]. For the optimal distribution of available resources, they propose to use a mathematical apparatus based on portfolio theory. As a criterion of optimality, the parameter of minimizing the financial costs of the enterprise is proposed. Inesa Khvostina, Nataliia Havadzyn, Liliana Horal and Nataliia Yurchenko in [15] proposed an approach to risk assessment taking into account the manifestation of emergent properties and using the method of taxonomy and factor analysis, which involves building economic and mathematical models that take into account qualimetric and structural components of the production process.

However, solution of the issues on increasing the reliability level of gas pipelines operation in the context of ensuring the country's own energy security requires further studying. Therefore, practical modeling and prediction of the reliability indicators of gas pipelines at the gas transmission enterprises require careful study and analysis.

3 Results and discussion

As an applied field of knowledge, the science of reliability is based on fundamental mathematical and natural sciences. It studies the patterns of change in the quality of technical devices and systems and provide its trouble-free exploitation with the minimum time and resources expense.

The reliability of gas transmission lines, like any technical object, is defined as the ability to perform the specified functions, while maintaining the specified performance over time. However, being a complex feature, depending on the purpose and conditions of operation, reliability may include failure-free, durability, maintainability or certain combination of these features.

The specific features of reliability are: (1) the time factor as the change in initial parameters during the operation of the equipment is estimated, (2) an object behavior prediction that maintains its original parameters (quality indicators).

The reliability of the gas supply system, its subsystems and facilities depends on many factors, among which are the following:

- the level of reliability of the elements of the equipment included in the system;
- the operation and management level of the system;
- the composition of the elements included in the system and the structure of the relations between them;
- the amount and structure of gas reserves;
- management efficiency.

The reliability and technological characteristics of the elements of these systems (average time of emergency and scheduled repairs, await repair time, the elements performance) largely depend on the quality of the equipment and the level of operation of the system. The values of these parameters are limited by the level of scientific and technological progress achieved and the economic feasibility of additional costs for the technology improvement. These factors can change both through the rational use and allocation of costs for the system's creation and development, as well as the costs for reserves, and also by increasing of these costs. So, reducing the reliability level of the gas pipeline results both in the weakening of the economic security of the state and in the fatal consequences for humans.

When planning repairs, upgrades and reconstruction of gas transmission lines it is important to prevent gas pipeline failures and crashes. Therefore, it is necessary to pay the greatest attention to the amount of equipment depreciation of the linear part of the pipeline. However, the service life can be extended as a result of inspections and diagnostics of the technical condition of the gas pipelines. That's why it is necessary to take into account the volume of natural gas transportation planned; safety of gas transmission lines; gas pipelines demolition.

The main characteristics of the gas transmission lines reliability: trouble-free, durability and maintainability.

We have determined that gas transmission lines may be in one of the following states: (1) loaded, (2) scheduled preventive repair, (3) forced (emergency) idle time. As a result of the influence of various external connections of a random nature, the gas transmission lines in the process of exploitation passes from one state to another. The transition is made at random times. Only sometimes it is possible to predict the exact residence time of gas transmission lines. But even so, there is uncertainty about the onset of the moment of change of state.

The stability of the gas transportation system is determined by the material base, which includes the gas-pumping machinery and the linear part of the main gas pipelines. Only highly qualified personnel can satisfy the needs of its high efficiency and reliability. Predictions of gas pipeline failures and rapid elimination of the consequences of accidents are particularly relevant at modern, powerful gas pipelines.

Determination of economic losses caused by accidents is important for the gas transmission company. Economic risks are not subject to mandatory assessment by supervisory authorities. Therefore, the permitted levels of these risks are not regulated. The economic risks assessment model based on economic feasibility and efficiency of gas pipeline further operation was offered. We find the economic losses caused with the failures and accidents determination to be particularly important for gas transmission companies.

We offer to determine the enterprise's economic losses by the following steps.

1. The main losses from failures of a gas pipeline are the cost of direct gas losses *Ld*, losses during gas pipeline downtime *Ldt* and the repair cost *Lr*. It also includes losses from possible damage to technical facilities and communications, crossing the gas pipeline at the accident site *Lt* and the social costs caused by the possible people displacement or the restoration of buildings *Ls*.

2. Gas leakage losses from gas leak in monetary terms is:

$$Ld = (V1 + V2) \cdot Pg \quad (1)$$

where $V1$ – the volume of gas exiting the pipeline by the time the taps are closed;

$V2$ – the volume of gas exiting the pipeline after the taps have been closed until the pipeline is fully released;

Pg – the price of 1 cubic meter of gas.

3. Losses during gas pipeline downtime *Ldt*:

$$Ldt = Kdn \times Vd \times Pg + Pp \quad (2)$$

where *Kdn* – downtime, days;

Vd – daily volume of gas transportation;

Pp – the penalties according to the contract.

The repair cost depends on the type of failure, the amount of equipment involved, the availability of the facility and the repair type.

4. Losses from possible damage to technical facilities and communications include the amount of compensation for repair or the losses incurred by the pipeline owner if these facilities are on his balance sheet.
5. Social loss is associated with the possible displacement of people or the restoration of social facilities that have been affected by the failure. Economic social losses are estimated if a threat to social objects that border or are in the natural areas of the main gas pipelines affected. The magnitude of these losses depends on the type of failure and the distance to the social object. In the case of insurance policies, the total loss may be reduced by the amount of insurance claims.

Therefore, by determining the economic losses by individual components, gas transportation companies will be able to determine the order of precautionary feasibility measures to minimize costs.

The analysis of statistical data for 2016-2018 showed that the current state of the GTS enterprises of Ukraine is a reflection of the general economic crisis phenomena. More than 50% of gas pipelines have been operated for over 30 years.

The structure of gas pipelines in terms of service includes: up to 10 years – 3%; 10–15 years – 5%; 16–20 years – 9%; 21–30 years – 32%; over 30 years – 51%. Powerful gas pipelines such as “Soyuz”, “Progress” and “Urengoy-Pomary-Uzhgorod” were built and used for transit only. Most of the compressor stations of these gas pipelines have imported high-tech equipment, but a large part of it already requires to be changed or renovated. More than 700 gas pumping units installed at compressor stations of gas pipelines of Ukraine. Almost 30% of them have already passed the final date of its exploitation period according to the documents. The consequence of this situation is a rather low effectiveness of functioning of the units, their efficiency coefficient of 24–26%, an overconsumption of fuel gas, and, accordingly, a decrease in the productivity and reliability of the main gas pipelines operation, which, in general, will have a negative impact on the energy security over the years.

Accidence is a contrast to a reliable energy transportation process. The largest number of accidents on gas transmission lines occurs due to defects in pipe metal, as well as to violations of the rules of gas transmission systems operation, arising as a result of poor-quality welding of patches when cutting openings for the installation of rubber balls. Many accidents are caused by temperature deformation of the gas pipeline.

The failure rate of gas pipelines shows an indicator λ(t), which can also show the intensity of failures [17].

$$\lambda(t) = \frac{n}{\Delta t n(t) L}, \tag{3}$$

where n – the number of failures during Δt over the entire length of the pipeline;

$n(t)$ – the number of non-failing elements by the time t;

L – the length of the pipeline.

For main gas pipelines, this value is given depending on the diameter as the ratio of the number of days of emergency status to the entire period of operation (year). For main gas pipelines, this value is given depending on the diameter as the ratio of the number of days of emergency status to the entire period of operation (year). The failure rate also depends on the number of lines and the diameter of the pipeline (table 1).

Table 1. The dependence of the failure rate of the gas transmission lines on the number of pipes and their diameter (based on [12]).

Diameter, mm	The failure rate (at 1/hour*10^{-3}) for different lines number N			
	N=1	N=2	N=3	N=4
1020	17,8	27,4	35,9	43,6
1220	24,6	38,1	49,9	60,4
1420	32,6	50,2	65,5	79,5

For example, here are sections consisting of several lines of gas pipelines in the territory of Western Ukraine, namely: gas pipelines “Belchevolitsa-Dolina” and “Ivacevichi-Dolina-III”; gas pipelines “Bogorodchany-Dolina – “Torzhok-Dolina”; gas pipelines “DUD-I”, “DUD-II” and “Progress”; gas pipelines “Pasichna-Dolyna”, “Bogorodchany-Dolyna”, “UPU” and “Soyuz”; gas pipelines “Uhersko-Ivano-Frankivsk”, “Uhersko-Ivano-Frankivsk-Chernivtsi”, “Pukenichi-Dolyna” and “KZU-II” and others.

It is possible to approximate the failure rates for pipelines of other length using the following coefficients (table 2).

Accidents and failures on gas transmission lines are discrete quantities that are independent of each other, and this allows us to predict these figures with the help of a statistical and mathematical apparatus. Thus, we have determined that the statistics on the failure of the linear part of gas pipelines are quite consistent with the exponential probability distribution function.

Table 2. Coefficients for determining the failure rate of gas pipelines of different lengths (based on [12]).

Length, km	The number of pipes *N*, diameter, mm		
	***N*=1 *d*=1020**	***N*=2 *d*=1220**	***N*=3 *d*=1420**
1000	1,0	1,0	1,0
2000	1,53	1,58	1,60
3000	2,00	2,08	1,15

The additional verification of the exponential distribution law compliance with the actual data for the calculations fully confirmed the assumption formulated in the paper about the probability distribution law and a number of the following important properties:

- time between gas pipeline failures is described by exponential law:

$$F_1(t) = 1 - e^{-\lambda t} \tag{4}$$

with a distribution density:

$$f_1\,(t) = \lambda e^{-\lambda t} \tag{5}$$

- the probability of the number of failures in a gas pipeline of length L in a single gas line at time T is described by Poisson's law:

$$p\{n\} = \frac{(\lambda LT)^n}{n!} e^{-\lambda LT} \tag{6}$$

where λ is a constant positive value.

- the failure rate of the commissioned gas pipelines decreases monotonically over time, and the failure rate increases over time for gas pipelines operated for more than 20 years.

Our additional studies have shown that in most cases it is possible to use an exponential representation of the law of distribution (fig. 1).

Recovery time distribution function is represented as:

$$F_{2\,(t)=1-e^{-\lambda t}} \tag{7}$$

and can be used to build methodological bases for reliability assessment.

The failure rate increases with the length of the pipeline, its corrosion etc. Our processing of a large number of statistics shows the existence of a linear relationship between the specific failure rate and the diameter of the pipeline:

$$\lambda = a_1 d + b_1 \tag{8}$$

The coefficients *b* here were determined based on the built-in functions of the trend curves of the Excel and are relevant $a_1 = 0{,}89\cdot 10^{-10}$; $b_1 = 0{,}987\cdot 10^{-8}$.

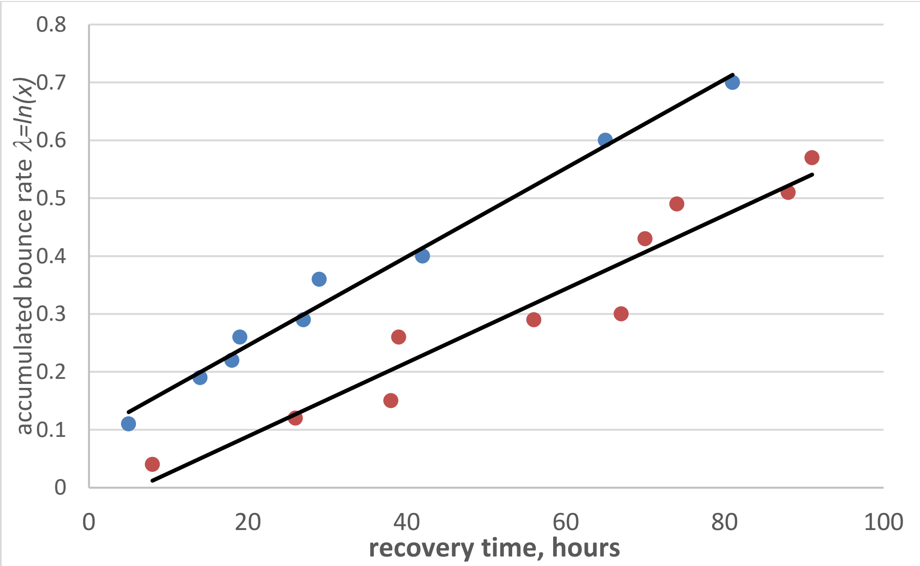

Fig. 1. Direct correspondence of experimental data to the exponential law of distribution of the operating time of the linear part of gas pipelines: 1 – diameter 1220 mm; 2 – diameter 1420 mm [30].

Fig. 2, 3 (based on the commercial statistics of Western Ukrainian Gas Pipelines Department for 2017-2018) shows the results of the study: a graphical interpretation of the dependence of (a) the failure rate and (b) the average recovery time from the diameter of the pipeline for the actual data and their trends. As we can see, we have a high accuracy of getting theoretical dependencies on the actual data. As we can see, the actual data are highly correspondent to theoretical trends.

To estimate the intensity of failures $\lambda(t)$ different methods can be used. For the linear sections of pipeline the approaches used in [21] allow, on the basis of information on the displacement for a certain set of surface points of the studied body, to determine the law of motion of each point of the investigated pipeline in the form:

$$\vec{r}\,(s,\varphi,r,t) = \vec{r_l}(s,\varphi,r,t) - R\,\vec{n_l} +$$
$$+\rho(s,\varphi,r,t)\big[\cos\omega(s,\varphi,r,t)\cdot\vec{b_1} + \sin\omega(s,\varphi,r,t)\,\vec{n_l}\big] + \psi(s,\varphi,r,t)\vec{L_l} \quad (9)$$

where $\rho(s,\varphi,r,t)$ $\omega(s,\varphi,r,t)$ $\psi(s,\varphi,r,t)$ – functions that characterize the points movement of the body studied in radial, transverse and longitudinal directions;

variables s,φ,r – are related to a curvilinear coordinate system:

s – coordinate along the axis of the body, $0 \le s \le L$;

φ – coordinate in the polar angle, $0 \le \varphi \le 2\pi$;

r – coordinate for the radius of the pipeline: $R_{int} \le r \le R_{out}$, $R_{вн}$ – internal and $R_з$ – the outer radius of the pipe,

$\vec{n_l}.\vec{b_1}\,,\vec{L_l}$ – components corresponding to normal, binormal and tangent at the studied point of the body.

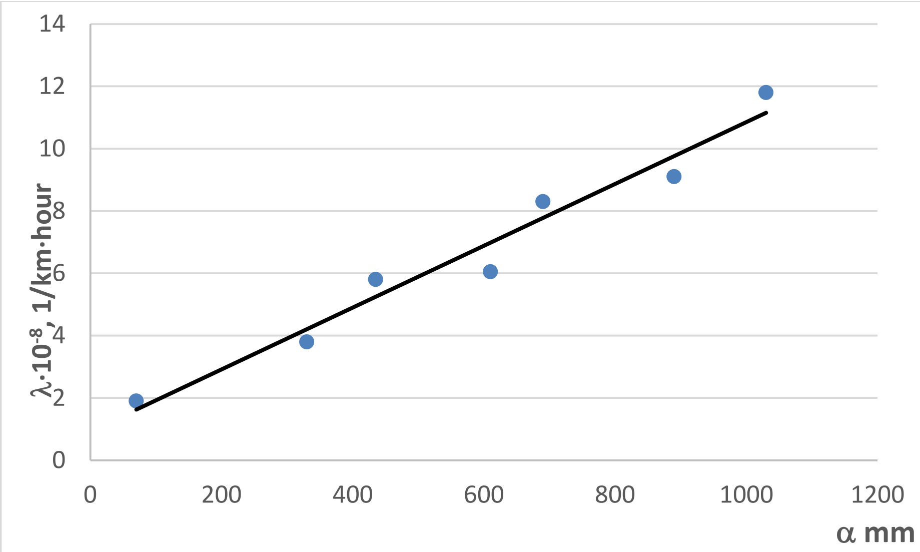

Fig. 2. The dependence of the specific failure rate on the diameter of the pipeline.

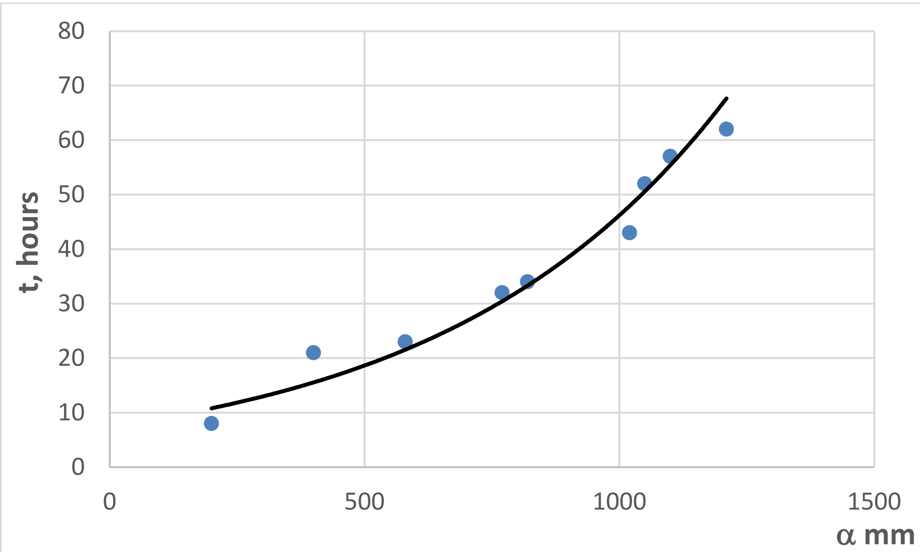

Fig. 3. The dependence of the average recovery time on the diameter of the pipeline.

The formula (3) is valid for a quasi-linear section of objects. In [21; 30] the ideas are given for conical and spherical sections of pipelines used in various industrial systems. The presentation of the form (1) allows us to calculate the change of the stress-strained state of the studied objects within the model of a stress-strained isotropic or anisotropic body using the formulas [21]:

— for deformation tensor components:

$$\varepsilon_{ij} = \frac{1}{2}(\nabla_i w_j + \nabla_j w_i) \tag{10}$$

where w_i – components of the displacement vector calculated by (1);

∇_i – covariant differentiation operator in the corresponding coordinate system (Cartesian, cylindrical, conical, orthogonal) [30];

— for stress tensor component (isotropic model):

$$\sigma^{ij} = \lambda I_1(\varepsilon_{ij}) g^{ij} + 2\mu\varepsilon^{ij} \tag{11}$$

where $\sigma^{ij}, \varepsilon^{ij}$ – contravariants components of the strain and stress tensor;

s,φ, r – pseudopolar coordinates;

$I_1(\varepsilon_{ij})$ – the first invariant of the strain tensor:

$$I_1(\varepsilon_{ij}) = \sum_{ij=1}^{3} \varepsilon_{ij} g^{ij} \tag{12}$$

$$\mu = \frac{E}{2(\sigma+1)} \text{ and } \lambda = \frac{E\sigma}{(1+\sigma)(1-2\sigma)} \tag{13}$$

— for stress tensor component (isotropic model):

$$\sigma_{ij} = \sum_{k,l=1}^{3} C_{ijkl}\varepsilon_{kl} \tag{14}$$

where C_{ijkl} – components of the elastic module tensor, there is a relationship between the covariant and contravariant components of the tensor:

$$\varepsilon^{kl} = \sum_{i,j=1}^{3} \varepsilon_{ij}\, g^{ik} g^{jl} \tag{15}$$

On the fig. 4 it is shown that zones off potential section's failure can be defined as zones of great stresses change – greater than critical value 400 MPa.

It is possible to realize the technology (3)-(9) to calculate the stresses changing in different moments of time. If *N* – the total number of points, in which the stresses changing is defined, *M* – the total number of points, in which the value of tresses changing is greater that valid values, the value $\lambda(t)$ can be estimated as.

$$\lambda(t) = {}^{M}/_{N} \tag{16}$$

The analysis of the results showed that when the diameter increases, the increase in λ can be explained by the following reasons:

— when the weight of the pipes increases, loading and unloading operations become more complicated, raising the likelihood of damage to the pipes during such operations;
— joining of pipes during welding when the diameter increases is complicated even if the specified technical conditions are observed. The radius of the pipeline sag bend increases with an increase in the diameter, which sometimes causes difficulties

when laying pipelines in a trench at the turns of the route and results in appearance of increased stress;

— the temperature regime of large-diameter gas pipelines during operation is more severe than the temperature regime of small-diameter pipelines, which can lead to thermal deformations.

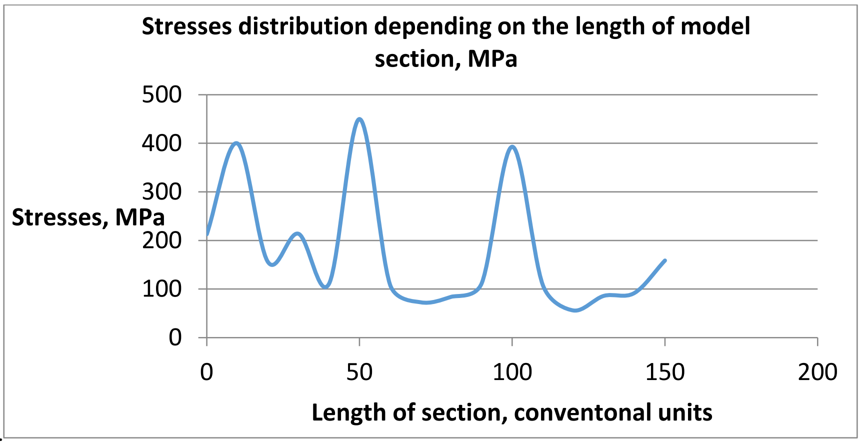

Fig. 4. Stresses distribution depending on the length of model section, MPa (based on [19]).

The next important indicator of the gas pipeline reliable operation is the mean time to recovery, which is determined by formula (15), or the recovery rate of μ, which is the inverse value of the mean time to recovery.

$$t_{av} = \frac{1}{n}\sum_{i=1}^{n} t_i \tag{17}$$

where t_i is the time of liquidation of the i-th accident;

n is the total number of accidents.

The recovery time depends on the nature of the accident, time of the year, conditions of the gas pipeline route, distance between the accident scene and emergency repair station, equipment of the emergency team with transport, machines, and mechanisms, as well as qualification of the personnel involved in the reproduction process. The time for repair of the same diameter gas pipeline varies widely. However, the dependence of the mean time to recovery on the diameter can be approximated by the following dependence:

$$t_{av} = a_2 d^2 + b_2 \tag{18}$$

The values of the coefficients b (18) are determined by prediction. We obtained the following results: $a_2 = 3.07\cdot 10^{-5}$; $a_2 = 8.97$.

The graph (fig. 3) shows the curve of dependence (18), as well as the actual values of t_{av} obtained as a result of processing the statistical data. When the diameter increases, the growth of t_{av} is explained by the following reasons:

- the length of the pipeline rupture increases with an increase in the diameter leading to a growth in the volume of repair works;
- an increase in the diameter results in a growth in the volume of excavation and welding works;
- joining of pipes during repair works on large-diameter gas pipelines becomes sharply more complicated and takes a large share of the total time spent for accident elimination.

Financial losses from accidents are considered to be one of the main characteristics that determine the strategy for financing the LSMGP repair works. Prediction of the amount of losses in the gas pipeline section in the event of accidents determines the priority in financing the repair works of the section. Taking into account the fact that the cost of gas is growing, it is necessary to determine the financial losses of an enterprise from the volume of the lost gas, as well as the main factors that led to occurrence of accidents at the facilities under study. The complexity of the algorithm for assessing the losses from accidents at the LSMGP primarily consists in the fact that its value depends on many different factors (diameter of the gas pipeline, its length, laying conditions, age of the gas pipeline, etc.). Such circumstances induce to consider losses as a random variable.

Failure prevention is possible as a result of the high-quality repair service (works on replacement or repair of the gas pipeline, the parameter value of which approached the limit), which requires financial investments and highly educated personnel. The equipment, which is not only physically, but also morally obsolete (it results in frequent stoppages in work and emergency situations; the equipment is often operated in uneconomical modes), is now used in the system of transportation and storage of natural gas in Ukraine. This leads to an increase in consumption of the fuel and energy resources (FER), as well as to an increase in their prime cost and processing losses.

In order to predict further development of the gas pipeline defective areas by the time an emergency situation occurs, it is necessary to consider the amount of losses when it actually occurs.

We carried out statistical processing of the data on defects in gas pipelines based on in-line inspection (INI). It was found that the relative failure rate and overhaul work scope do not have a clear trend, which is determined by the crisis in the economy, decrease in the volume of natural gas transportation, and change in the pricing policy for the services of Naftogaz of Ukraine, NJSC.

The most important indicator characterizing the efficiency of operation of the main gas pipelines in the context of the country's energy security is the availability (reliability) coefficient.

In order to determine the tendency of this indicator to change, we carried out some prediction based on an expert survey of the following three groups of specialists: scientists, practitioners, and gas pipeline personnel.

In order to determine the numerical score of the complex indicator of the gas pipeline reliability as one of the main indicators affecting the energy security of the country, the methodology developed by Dow Chemical Co. and based on the relative index of gas pipeline reliability (relative index of pipeline safety – RIPS) was taken as a basis [18]. This criterion is determined using 5 indices. Four of them (F_1, ..., F_4) characterize the most typical causes of the line section failures, which include anthropogenic influences, corrosion, design errors, and operational control errors. The fifth α characterizes the severity of the consequences in emergency situations.

We improved and detailed this methodological approach for reliability assessment, as well as filled table 3 with the indicators that describe the most common causes of failures on the gas pipelines in the Western region of Ukraine.

Thus, based on the developed-by-us assessment of the reliability of the line section of the main gas pipelines, we will get the complex indicator of the LSMGP availability characterizing the reliability and calculated using formula (19):

$$K_q = \sum_{i=1}^{11} \beta_i \cdot F_i \quad (19)$$

where β is the probability of emergency situation occurrence at the i-th factor influence.

After applying the study results with the help of the expert assessments, we will obtain the following dependence that is typical for the enterprises in the Western region (Dolyna LPDMGP is taken as an example):

$$K_q = 0{,}11F_1 + 0{,}1F_2 + 0{,}1F_3 + 0{,}1F_4 + 0{,}07F_5 + 0{,}09F_6 + 0{,}1F_7 + 0{,}09F_8 + \\ + 0{,}09F_9 + 0{,}08F_{10} + 0{,}07F_{11} \quad (20)$$

Table 3 shows the procedure for calculating the indicators, with the help of which it is possible to quantitatively represent the factors that affect the occurrence of failures and accidents on the line section of the main gas pipelines reducing their reliability. As can be seen from the above Table 3, one of the indicators that affect the complex indicator of the gas pipelines reliability is the coefficient of serviceability. Let's predict its value for the period of 2020-2035. Let's consider the scenario approach that provides for realistic and optimistic predictions (tables 4 and 5). The first one involves predicting the coefficient of serviceability based on the statistical data from different gas transmission enterprises using linear regression. The second one consists in making investments into the GTS, its modernization, and human development. The investments into human development should be considered by an enterprise as one of the priority tasks of its strategy.

Therefore, according to the provided predicted data based on the second scenario (table 5), the gas transmission enterprises of the Western region will be able to significantly improve the indicator of the gas pipeline operation reliability that will reach the value of 0.68 in 2035, which is 0.1 higher than the value according to the predicted data based on the first scenario.

Since the processes of gas transportation and storage are considered to be energy-intensive (the share of expenses for the FER in the total prime cost of gas transportation is 60-80%) and has a direct impact on the energy security of our country, the priority for an enterprise is to carry out technological production re-equipment, i.e. improvement of technologies, which is not possible without highly professional personnel. At present, the cost of labor is determined by the following quality characteristics: intelligence, education, and professionalism [2; 23; 29].

Table 3. Factors and indicators of their measurement affecting gas pipelines operation reliability.

Factor	Designation	Indicator calculation algorithm
Quality of the works on the gas pipeline construction	F_1	Ratio of the volume of the works on the gas pipeline construction carried out in compliance with the construction instructions and standards to the total volume of the works on the gas pipeline construction
Quality of the gas pipelines repair service	F_2	Ratio of the volume of the repair works carried out in compliance with the requirements and standards to the total volume of the gas pipelines repair works
State of the gas pipeline insulation coating	F_3	Ratio of the length of the gas pipelines covered with the suitable insulation coating to their total length
Level of the gas pipeline corrosion failure	F_4	Ratio of the number of the defective corrosion damages on the pipe body to the length of gas pipelines
Natural-and-geographical location and laying environment of gas pipelines	F_5	Depth, at which the gas pipeline is located; Atmospheric conditions (temperature, humidity); Possibility of ground distortion; Possibility of uneven soil compaction; Possibility of erosion of the gas pipeline due to flooding or changes in the river bed
Level and quality of the gas pipeline inspection and cleaning	F_6	Ratio of the length of the gas pipelines that have passed the in-line inspection and cleaning to the total length of gas pipelines
Qualification level of the repairmen, engineers, and other technical workers	F_7	Ratio of the number of the engineers and other technical workers that correspond to the position held according to the certification results to the number of the employees who have passed the certification
Coefficient of serviceability of the main gas pipelines, fraction unit	F_8	Ratio of the weighted service life of gas pipelines to the average standard service life of gas pipelines
Level of sophistication in making management decisions on operation and restoration of main gas pipelines	F_9	Ratio of the number of correct and timely made management decisions to the total number of the management decisions related to the process of operation and restoration of gas pipelines
Level of pipe defects	F_{10}	Ratio of the volume of the used pipe with some factory and mechanical defects to the total volume of the used pipe
Level of protection of gas pipelines	F_{11}	Ratio of the length of the gas pipelines protected against corrosion with the help of electrochemical protection to the total length of gas pipelines

Table 4. Prediction of the coefficient of serviceability based on the first scenario.

Predicted values				Years				
2020	2025	2030	2035	2013	2014	2015	2016	2017
0.58	0.54	0.56	0.58	0.68	0.66	0.640	0.526	0.618

Table 5. Prediction of the coefficient of serviceability based on the second scenario.

Predicted values				Years				
2020	2025	2030	2035	2013	2014	2015	2016	2017
0.65	0.65	0.66	0.68	0.68	0.66	0.640	0.526	0.618

In order to improve the reliability indicators of the Ukrainian GTS functioning in the context of energy security, we propose to introduce the following [28]:

A) system of technical and technological measures:

- Modernization and replacement of pipelines.
- Improvement of the anti-corrosion protection.

These measures will allow to prevent emergency situations on the line section of the gas pipelines, increase their resistance to adverse natural and climatic conditions, as well as reduce gas pollution during transportation (prevention of deterioration of quality parameters) and gas leaks. All of this will lead to optimization of the system as a whole, as well as to reduction of the FER losses, and, hence, total expenses of an enterprise.

- Introduction of new energy-efficient engines. The largest portion of the engines that drive compressor stations (hereinafter referred to as CS) is made by gas turbine engines, the efficiency coefficient (efficiency) of which is very low and does not even reach 25%, therefore, it is necessary to replace them with more energy-efficient engines (the efficiency of which is higher). A sufficient niche of manufacturers of gas turbine engines (GTE) with the best technical quality parameters and greater efficiency formed on the domestic market.
- Reduction of energy losses associated with the change in the load of gas pipelines and achievable by increasing the level of automatic control and regulation of CS operation, as well as by introducing the automated systems for enabling and disabling a gas-pumping unit (GPU).

B) The necessary prerequisite for implementation of the above measures is the fulfillment of a number of socio-economic tasks, the results of which will make the basis for their realization. In particular, in order to control the deviations of the FER consumption rates, it is necessary to develop and establish them first, therefore, the first of the socio-economic measures should be the following [6; 11]:

1. Development of economically justified norms of the FER specific consumption rate. In order to do this, it is suggested to conduct an in-depth analysis of available equipment, study technical characteristics, determine optimal operating and

loading modes, as well as develop economically justified norms of the FER consumption rate on the basis of the comprehensive knowledge obtained.
2. Introduction of the system of stimulation and personal responsibility of employees. Material stimulation for an efficient use of energy resources, carrying out of the work to improve the efficiency of using the FER, introduction of different energy-saving technologies, etc. by awarding the employees with bonus payments within the established share of the cost of the saved FER will lead to the material interest of each employee, since the economic result of the whole enterprise will depend on their work.
3. The efficient and flexible management system capable of making operational management decisions on effective business activities in various conditions should become the quintessence of the work of a gas transmission enterprise in the market conditions.

4 Conclusions

The statistical models for calculation of the gas pipelines reliability indicators were obtained on the basis of actual data on the gas pipelines operation in the context of the country's energy security. Utilization of these models made it possible to carry out a prediction based on the partial indicators and make adjustments to the system of gas pipelines maintenance, which will increase their operational reliability and energy security of Ukraine.

Justification of effective management decisions and reforms requires accuracy not only of the relative quantitative assessment of the reliability level of gas supply and impact of individual threats, but also of the absolute and qualitative assessment, which will allow modeling individual scenarios of the measures for the reform implementation. Constant monitoring and use of the predicted parameters of the gas pipelines state will provide a possibility to reduce the accident rate on main pipelines, save significant financial resources, and obtain an economic effect due to the system of technical, technological, economic, social, and environmental measures. Since the indicators of the gas pipelines operation reliability are influenced by a significant number of different factors, it is very difficult to assess the influence of each of them individually and in a complex, therefore the methods for statistical modeling and prediction are suggested to be utilized. When using them, it is possible to take into account the influence of all the factors on the reliability indicators, on which the functioning of the gas transportation system, as well as the energy security of Ukraine, will largely depend.

References

1. Abolhosseini, S., Heshmati, A., Rashidghalam, M.: Energy security and competition over energy resources in Iran and Caucasus region. AIMS Energy **5**(2), 224–238 (2017). doi:10.3934/energy.2017.2.224
2. Andrusiv, U., Kinash, I., Cherchata, A., Polyanska, A., Dzoba, O., Tarasova, T., Lysak,

H.: Experience and prospects of innovation development venture capital financing. Management Science Letters **10**(4), 781–788 (2020). doi:10.5267/j.msl.2019.10.019

3. Belvederesi, C., Thompson, M., Komers, P.: Canada's federal database is inadequate for the assessment of environmental consequences of oil and gas pipeline failures. Environmental Reviews **25**(4), 415–422 (2017). doi:10.1139/er-2017-0003
4. Bushmeleva, K.I., Plyusnin, I.I., Bushmelev, P.E., Uvaisov, S.U.: Distributed wireless system for monitoring the technical state of objects in a gas-transport network. Measurement Techniques **56**(3), 226–231 (2013). doi:10.1007/s11018-013-0184-3
5. Butler, E.: Conclusion: Central and eastern European energy security - more than Russia. In: Ostrowski, W., Butler, E. (eds.) Understanding Energy Security in Central and Eastern Europe: Russia, transition and national interest, pp. 222–231. Routledge, London (2018). doi:10.4324/9781315651774
6. Cherchata, A., Popovychenko, I., Andrusiv, U., Simkiv, L., Kliukha, O., Horai, O.: A methodology for analysis and assessment of business processes of Ukrainian enterprises. Management Science Letters **10**(3), 631–640 (2020). doi:10.5267/j.msl.2019.9.016
7. Dergachova, V., Pysar, N.: Implementation of the market approach to the processes of management of the energy sector of Ukrainian economy under conditions of European integration. Eastern-European Journal of Enterprise Technologies 3(3-93), 40–49 (2018). doi:10.15587/1729-4061.2018.133437
8. Eser, P., Chokani, N.: Abhari, R.: Impact of Nord Stream 2 and LNG on gas trade and security of supply in the European gas network of 2030. Applied Energy **238**, 816–830 (2019). doi:10.1016/j.apenergy.2019.01.068
9. Han, Z.Y., Weng, W.G.: An integrated quantitative risk analysis method for natural gas pipeline network. Journal of Loss Prevention in the Process Industries **23**(3), 428–436 (2010). doi:10.1016/j.jlp.2010.02.003
10. Hassan, M., Afridi, M.K., Khan, M.I.: Energy policies and environmental security: a multi-criteria analysis of energy policies of Pakistan. International Journal of Green Energy **16**(7), 510–519 (2019). doi:10.1080/15435075.2019.1593177
11. Ievdokymov, V., Lehenchuk, S., Zakharov, D., Andrusiv, U., Usatenko, O., Kovalenko, L.: Social capital measurement based on “The value explorer” method. Management Science Letters **10**(6), 1161–1168 (2020). doi:10.5267/j.msl.2019.12.002
12. Ilkevich, N.I., Dzyubina, T.V., Kalinina, Z.V.: Development of analysis methods for ensuring the reliability of gas distribution systems in the problems of complex energy supply. E3S Web of Conferences **102** 02005 (2019). doi:10.1051/e3sconf/201910202005
13. Ivanov, O., Avdeuk, O., Bushmeleva, K., Ivanov, I., Uvaysov, S.: Model for calculating the reliability of a wireless sensor telecommunication system for monitoring the gas transmission network state. Paper presented at the Moscow Workshop on Electronic and Networking Technologies, MWENT 2018 - Proceedings, 1-5 March 2018. doi:10.1109/MWENT.2018.8337229
14. Kharlamova, G., Stavytskyy, A.: Economic Modeling of Energy Security: Simulation of Economic Processes (Case of Ukraine Gas system). CEUR Workshop Proceedings **2104**, 128–143 (2018)
15. Khvostina, I., Havadzyn, N., Horal, L., Yurchenko, N.: Emergent Properties Manifestation in the Risk Assessment of Oil and Gas Companies. CEUR Workshop Proceedings **2422**, 157–168 (2019)
16. Luo, Z., Xi, Y., Wang, H.: Research on comprehensive quantitative risk-assessment of urban nature gas pipeline. Paper presented at the International Conference on Management Science and Engineering - Annual Conference Proceedings, 2196-2202

(2013). doi:10.1109/ICMSE.2013.6586568
17. Manian, L., Hodgdon, A.: Pipeline integrity assessment and management. Materials Performance **44**(2), 18–22 (2005)
18. Oliinyk, A., Chernova, O.: Estimation of gas losses based on the characteristics of the state of wells of Dashava storage. Eastern-European Journal of Enterprise Technologies 6(8-90), 25 – 32 (2017). doi:10.15587/1729-4061.2017.116806
19. Oliinyk, A., Robur, L., Yarovoj, K.: Determination of stress-deformation state of vibrating constructions by fiber laser Doppler anemometer. III International Conference of Vibration Measurements by Laser Techniques: Advances and Applications, Ancona, Italy, Proc. SPIE **3411**, 404–407 (1998)
20. Oliinyk, V., Kozmenko, O.: Optimization of investment portfolio management. Serbian Journal of Management **14**(2), 373–387 (2019). doi:10.5937/sjm14-16806
21. Oliynyk, A.: Mathematical models for the process of quasi-stationary deformation of pipeline and industrial systems when changing their spatial configuration. IFNTUOG, Ivano-Frankivsk (2010)
22. On the National Security Strategy of Ukraine. https://zakon.rada.gov.ua/laws/show/n0008525-15 (2015). Accessed 17 Aug 2015
23. Popadynets, I., Andrusiv, U., Shtohryn, M., Galtsova, O.: The effect of cooperation between universities and stakeholders: Evidence from Ukraine. International Journal of Data and Network Science **4**(2), 199-212 (2020). doi:10.5267/j.ijdns.2020.1.001
24. Sharples, J.D.: The International Political Economy of Eastern European Energy Security: Russia, Ukraine, and the European Union. In: Davidson, D.J., Gross, M. (eds.) Oxford Handbook of Energy and Society, pp. 137–164. Oxford University Press, Oxford (2018). doi:10.1093/oxfordhb/9780190633851.013.7
25. Shmygol, N., Łuczka, W., Trokhymets, O., Pawliszczy, D., Zavgorodniy, R.: Model of diagnostics of resource efficiency in oil and gas sector of economy of Ukraine. E3S Web of Conferences **166**, 13005 (2020). doi:10.1051/e3sconf/202016613005
26. Voynarenko, M., Dykha, M. V., Mykoliuk, O., Yemchuk, L., Danilkova, A.: Assessment of an enterprise's energy security based on multi-criteria tasks modeling. Problems and Perspectives in Management **16**(4), 102–116 (2018). doi:10.21511/ppm.16(4).2018.10
27. Yu, W., Gong, J., Song, S., Huang, W., Li, Y., Zhang, J., Hong, B., Zhang, Y., Wen, K., Duan, X.: Gas supply reliability analysis of a natural gas pipeline system considering the effects of underground gas storages. Applied Energy **252**, 113418 (2019). doi: 10.1016/j.apenergy.2019.113418
28. Zablodska, I., Akhromkin, Y., Akhromkin, A., Bielousova, L., Litvinova, I.: World experience in public administration of the transformation of energy-dependent regions in the context of their sustainable development. Problemy Ekorozwoju **15**(2), 235–244 (2020)
29. Zelinska, H., Andrusiv, U., Simkiv, L.: Knowledge economy: Trends in the world and analysis of Ukraine. Journal of Eastern European and Central Asian Research **7**(1), 104–113 (2020). doi:10.15549/jeecar.v7i1.325
30. Zelinska, H., Fedorovych, I., Andrusiv, U., Yurchenko, N.: Modeling of the Gas Transmission Reliability as a Component of Economical Security of Ukrainian Gas Transmission System. Advances in Economics, Business and Management Research **99**, 127–132 (2019). doi:10.2991/mdsmes-19.2019.25