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Structural Modelling of the Relationship Between the Vulnerability of Ukrainian Regions to COVID-19, Environmental Status and Factors of Readiness of the Medical System

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Abstract. The division of the regions of Ukraine into "red", "orange", "yellow" and "green" zones are the consequences of the differentiated regional impact of the pandemic caused by the COVID-19 virus, but the reasons for such different vulnerabilities have not been clarified yet. The purpose of the study is to construct a system of regression equations containing implicit variables that are common characteristics of industries and help to analyse relationships in a complex system. The methodological tools of the study were: review of current scientific trends using VOSViewer 1.6.10, the main component method, which allows selecting the most significant factors and model with structural equations that reflect the relationship between the three areas of activity. 25 oblasts of Ukraine were selected as the object of the study, since they have different levels of vulnerability to the pandemic and can become a model for studying the regional differentiation of any country. The study presents the results of an empirical analysis of the structure of three areas of activity of the country. Modelling of structural equations to establish the relationship between the factors of vulnerability of the regions of Ukraine from the COVID-19 pandemic, the environmental state and the state of readiness of the medical system is carried out. It is theoretically substantiated that there is a direct connection between the studied areas: environmental, medical and epidemiological, and that deterioration in one industry leads to deterioration in another. The results obtained prove that it is possible to influence the differentiated course of the pandemic, but not after the event. A consistent increase in funding from the state budget for healthcare would have a greater effect, with sufficient financial support for environmental protection. The choice of state strategies must be approached comprehensively, because a narrow reform of the system, such as medical, will not give the maximum effect, without an innovative policy in the field of ecology

Keywords: pandemic, econometrics, ecology, medicine, principal component method

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Introduction

The pandemic caused by the SARS-CoV-2 virus in China in 2019 forced a change in the direction of scientific thought and re-assessment of human values. In Ukraine, the first patient was identified on March 3, 2020, and as of April 6, 2021, 13,398 new cases were registered per day. Regional differentiation is of interest for the study, for example, 51, 99 and 85 new cases of the disease were registered per day in Chernihivska, Kirovohradska and Ivano-Frankivska Oblasts, respectively, but in Odeska, Lvivska, and Kyivska Oblasts there were 1,436, 1,105 and 1,432 new cases, respectively [1]. It is inappropriate to look for reasons in social behaviour, because such differentiation occurs within the same country, with the same mentality, culture, and social habits. The disease affects different people in different ways, for some it passes in a mild form, and for others hospitalisation with artificial lung ventilation is necessary. The pandemic also revealed weaknesses that existed in the medical sphere of any country or region, and pointed out the lack of provision of medical institutions to counteract the large influx of patients.

In order to counteract the consequences of the pandemic, the government of Ukraine has allocated additional funds for the healthcare sector, compared to previous years, 2.7 times more funds were allocated in 2020 compared to 2019 [2]. In general, there is a tendency to increase state budget expenses on healthcare during 2016-2021, which is a positive indicator of the government's attitude to the health of its citizens. In contrast to the healthcare sector, spending on the environmental sector during this period has decreased in dynamics, compared to 2016, the volume of spending decreased by 25% compared to 2020. The general trend of reducing funding for environmental protection with increased emissions into the air and water has a negative impact on the overall state of public health of citizens, which negates the increase in spending on healthcare that fights the consequences of poor ecology, viruses, bacterial diseases, etc.

The pandemic situation in Ukraine has revealed low financial security of most primary and secondary healthcare institutions and other unresolved problems related to the redistribution of funds between industries. That is why there is an urgent need to develop methodological approaches for choosing strategic decisions in the context of budget allocation among industries, taking into account the difficult epidemiological situation. Therefore, with the spread of the disease, there are more and more questions in the scientific community to which there is no clear answer.

Table 1. Expenditures from the state budget of Ukraine in the field of health and environmental protection, mln. UAH for 2014-2021

	Environmental protection	% of total expenses	Healthcare	% of total expenses
2014	2597	0.60%	10580.8	2.46%
2015	4053	0.70%	11450.4	1.98%
2016	4771.6	0.70%	12456.3	1.82%
2017	4739.9	0.56%	16729.1	1.99%
2018	5241.2	0.53%	22617.9	2.29%
2019	6316.2	0.59%	38561.6	3.59%
2020	6636.8	0.52%	124925.3	9.70%
2021 (by 1.04)	846.3	0.31%	34693.7	12.57%

Source: compiled by the authors based on [2]

The purpose of the study is to establish causal relationships between the environmental sphere, the readiness of medical institutions to receive a large number of patients and the vulnerability of Ukrainian regions to the COVID-19 pandemic.

This objective made it necessary to solve the following *tasks*:

– to form the optimal composition of indicators by performing the method of principal components, which can best describe the variability of such latent variables as ecology, medicine, and vulnerability of regions to the consequences of a pandemic;

– to develop a methodology for modelling structural equations of regional indicators of vulnerability to COVID-19, environmental status and readiness factors of the medical system;

– to study the relationship between the above factors, to establish the adequacy of the existing relationship;

– to assess the level of dependence of the studied parameters on each other.

Literature Review

The SARS-CoV-2 pandemic has forced a large number of scientists around the world to change the vector of scientific research. For example, the authors [3] investigate the causal relationship between a pandemic and environmental emissions through the introduction of quarantine restrictions in many countries around the world. The authors [4] are looking for causal links between the deterioration of people's psychological health and the pandemic. Researchers [5] proved a direct relationship between the state of atmospheric air pollution with solid particles and the risk of severe consequences of COVID-19, by performing the Poisson regression. The authors [6] proved that the severity of the disease in the first stages is directly proportional to the state of air pollution with solid particles, which negatively affects the human respiratory system. Therefore, indeed, many scientists have theoretically substantiated the relationship between the ecology of the region and the vulnerability of the population living there.

Regional differentiation was also considered in [7], the authors investigated mortality from COVID-19, identifying seasonal fluctuations in the context of one country, in order to predict the next waves of diseases. Researchers [8] have proposed models that offer an effective measure to prevent the spread of the disease while there is no herd immunity caused by vaccination. Scientists [9] used regression-correlation analysis to search for a link between the socio-economic vulnerability of the population, which is built based on the age structure of citizens, income level and commitment to maintaining social distance and the pandemic. In [10], the risk of a stock market collapse is analysed due to the growth of morbidity in the world and this dependence is theoretically substantiated. The team of authors [11] analyses the differentiated course of COVID-19 disease, and examines the cause of opioid use and race and ethnicity. The study [12] constructed a forecast of the course of the pandemic, taking into account the possible number of infections that are asymptomatic, because they further affect the prevalence of infection, due to their invisibility. Thus, a large number of studies are focused on finding causal relationships between the consequences of the pandemic on other areas of people's lives, apart from the deterioration of well-being.

The central place in many studies is occupied by the healthcare sector, which is first to accept negative consequences and is a litmus test of humanity's readiness to counteract the epidemic. Thus, in the study [13], the authors put in the first place the problem of medical personnel who are most likely to become infected and solve the problem by asynchronising the work of doctors. The researchers [14] made a detailed bibliographic description, in which the main subject is medical personnel, and especially nurses. The authors [15] developed an algorithm based on the Markov chain Monte Carlo to facilitate the systematisation of patient calls depending on the diagnosis of acute respiratory diseases in order to protect, first of all, medical personnel.

The analysis of scientific publications confirms that this topic related to the global pandemic, its causes, consequences and ways to overcome it is relevant. The VOSViewer 1.6.10 software was used to systematise and visualise case studies related to the concept of COVID-19. In Figure 1, 5 clusters of different colours and sizes are highlighted. The first group (Red) is associated with a person, social consequences, the occurrence of depression, cultural transformations, education. The second group (Green) is associated with healthcare, mutation, genetics, that is, the root cause of the virus. The next group (Blue) combines medicine, pharmacology, and ecology. The Yellow group indicates changes in the demographic structure of society, the quality of the air, and overall mortality. The Lilac group focuses on climate, tourism, and combines research metrics for research.

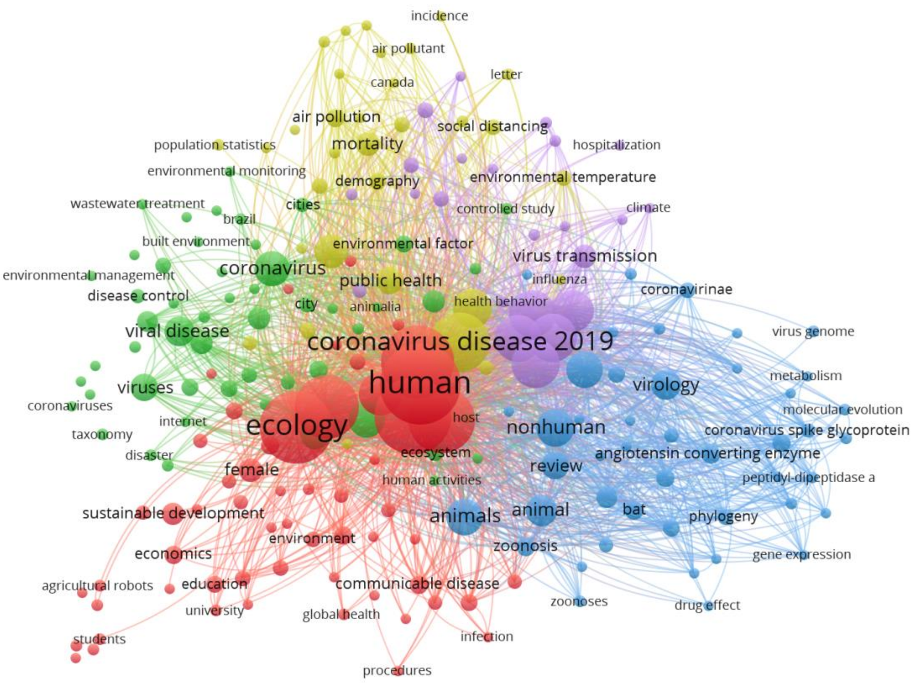

Figure 1. Distribution of the concept of "COVID-19" and related terms in publications was built using the VOSViewer 1.6.10 software

Figure 2 shows a diagram indicating the frequency of mention of the term "COVID-19" in scientific papers of different countries. The leaders are undoubtedly the United States, Great Britain, China, Canada and Italy. These countries are among the top-10 countries [1] affected by the pandemic, which is the reason for such interest among the scientific society.

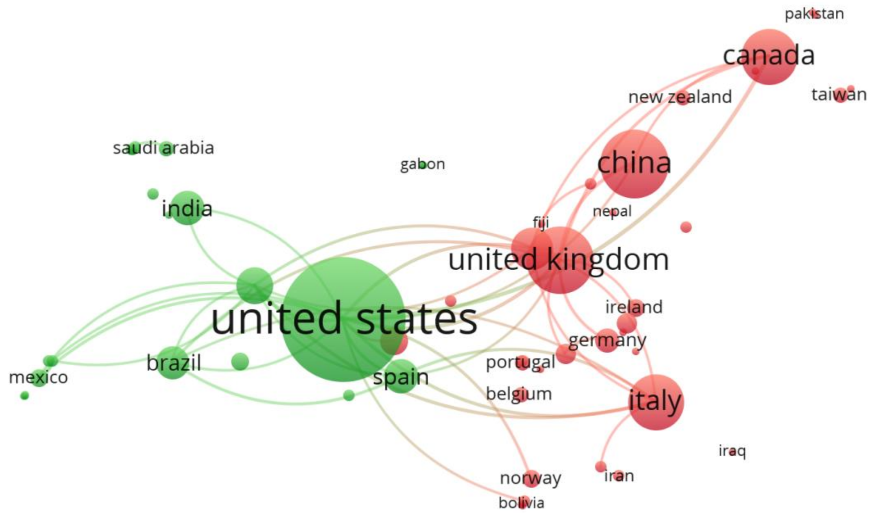

Figure 2. The territorial distribution of the use of the concept of "COVID-19" and related terms in publications is constructed using the VOSViewer 1.6.10 software

Materials and Methods

To achieve the purpose of the study, the following sequence of actions was chosen: collecting and analysing statistical data reflecting implicit variables – ecology, medicine, and vulnerability to the pandemic; conducting a method of principal components to select the most influential indicators; normalising data to minimise a large range of input data; conducting causal modelling with structural equations and checking the adequacy of the constructed model.

Stage 1. Collection and analysis of statistical data. 24 oblasts of Ukraine and the city of Kyiv were selected as the object of the study. At this stage, the identification of indicators that were most likely able to characterize the state of the environment (12 indicators) was carried out: costs and capital investments for environmental protection, the volume of waste generation, its disposal and incineration, emissions of pollutants into the atmosphere from mobile and stationary sources of pollution, carbon dioxide emissions, the volume of waste accumulated during operation in specially designated places [15]. The state of readiness of medical institutions was characterised by such indicators (11 indicators) [16] as the number of hospitalisations and contracts for medical services for the population under the programme of medical guarantees, the number of beds for hospitalisation and the volume of infectious diseases from them, the number of medical teams, infectious diseases specialists, anaesthesiologists, internists and junior medical personnel, the number of pharmacies that are places of the release of medicines by electronic prescriptions under the government programme "affordable medicines". The number of infected people (C_zahv), deaths (C_pomerlyh), and infectious beds occupied by patients with COVID-19 (C_lizhka) was selected as indicators of regional vulnerability from the pandemic [1].

To perform modelling with structural equations, a small number of explicit variables are used to form latent variables of a certain sphere of complex state structure. Therefore, a selection was made among a large number of obvious environmental and medical factors.

Stage 2. Factor analysis for selecting factors. Within the framework of the multivariate model and the absence of an explicit exogenous variable, the principal component analysis was performed to identify the indicators that most effectively demonstrated the variability of the entire structure. Eigenvectors and corresponding values were found to identify the least necessary number of variables that most fully characterised the medical and environmental spheres. The Principal Components & Classification Analysis module in STATISTICA software is used. Table 2 shows the result obtained when using the algorithm for constructing principal components. The first column indicates the number of factors that correspond to the component, that is, according to the Kaiser criterion, three indicators were selected for the study, for which the eigenvalue is greater than one, that is, it explains more than one variable. As a result, 88% of the total variance was explained by three variables: the number of contracts for medical care for the population under the medical guarantee programme (M_medgar), the number of anesthesiologists (M_anest) and the number of intensive care beds (M_lizhka). For environmental factors, two factors were selected in a similar way: emissions of carbon dioxide (E_diox) and pollutants from mobile sources of pollution (E_vykydy) into the atmosphere.

Table 2. Eigenvalues of vectors of 11 indicators of the medical services sector

	Eigenvalue	Cumulative eigenvalue	Percentage of cumulative variance
1	7.369417	7.36942	61.4118
2	1.734243	9.10366	75.8638
3	1.451868	10.55553	87.9627
4	0.938864	11.49439	95.7866
5	0.229066	11.72346	97.6955

Source: developed by the authors

Stage 3. Data normalisation. To perform modelling with structural equations, data normalisation is performed through a large data span (1):

$$\rho = x_{max} - x_{min} \tag{1}$$

where x_{max} – the highest value of a row of 25 oblasts of Ukraine, x_{min} – the lowest value of a row. Next, the study considers the minimax normalisation of data (2), which reduces all values to a range [0;1], where the value 1 – corresponds to x_{max}, and 0–x_{min}, while the general trend and variability of values are not lost.

$$x^* = \frac{x - x_{min}}{\rho} \tag{2}$$

This type of normalisation allows not losing the variability of factors and easily interpreting the results of the study, taking 1 for 100 %.

Stage 4. Modelling with structural equations. Having three groups of indicators: regional vulnerability to pandemic (*Cov*), environmental sphere (*Eco*) and readiness of medical institutions for a large influx of patients (*Med*), a system of simultaneous equations is used to describe a complex system and build causal relationships. The Cov index is chosen as an exogenous variable, and the general form of a system of structural equations is determined, which contains three latent variables that characterise the sphere as a whole and eight explicit independent variables and consists of nine linear equations (3):

$$\begin{cases} C_{lizh} = a_1 Cov + \partial_1, \\ C_{zahv} = a_2 Cov + \partial_2, \\ C_{pomerl} = a_3 Cov + \partial_3, \\ E_{vyk} = a_4 Eco + \varepsilon_1, \\ E_{diox} = a_5 Eco + \varepsilon_2, \\ M_{medgar} = a_6 Med + \varepsilon_3, \\ M_{anest} = a_7 Med + \varepsilon_4, \\ M_{lizhka} = a_8 Med + \varepsilon_5, \\ Eco = a_9 Cov + z_1, \\ Med = a_{10} Cov + a_{11} Eco + z_2. \end{cases} \tag{3}$$

where a_i, i=1..11 – the unknown coefficients, $\delta_{1,2,3}$, $z_{1,2}$, $\varepsilon_{1,2,3}$ – model errors and the free coefficients of the corresponding equations of the system of structural equations. Figure 3 shows a scheme of simultaneous equations in the form of the classical Lister Karl Joreskog model, consisting of three smaller composite models, but the greatest weight is the regression relationship between ecology (*Eco*), medicine (*Med*), and pandemic (*Cov*).

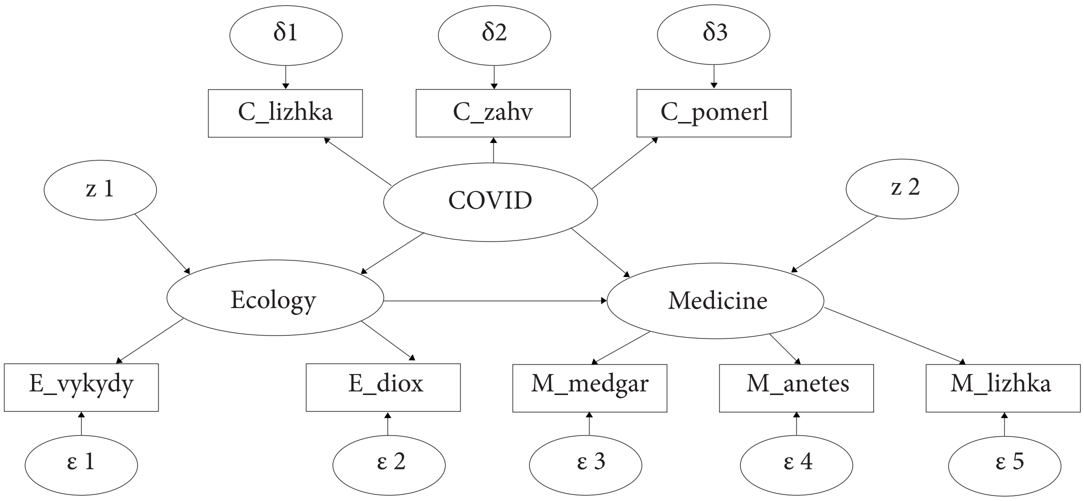

Figure 3. General scheme of the structural equation model for studying the relationship between the development of medical, environmental state and regional vulnerability to the pandemic

Source: developed by the authors

Results and Discussion

The study uses 8 explicit variables, the relationships between which are quite complex. By constructing implicit (latent) variables that characterise the entire sphere completely, it is possible to find connections between hidden variables. Explicit variables will be considered the consequences of the complex influence of latent ones, assuming the presence of errors. Using the above algorithm, the solutions of system (3) are found, which are represented in system (4):

$$\begin{cases} 1)\ C_{lizh} = 0{,}212 Cov + 0{,}014, \\ 2)\ C_{zahv} = 0{,}222 Cov + 0{,}029, \\ 3)\ C_{pomerl} = 0{,}231 Cov + 0{,}001, \\ 4)\ E_{vykydy} = Eco + 0{,}018, \\ 5)\ E_{diox} = 0{,}552 Eco + 0{,}07, \\ 6)\ M_{medgar} = Med + 0{,}028, \\ 7)\ M_{anest} = 1{,}089 Med + 0{,}024, \\ 8)\ M_{lizh} = 1{,}096 Med + 0{,}013, \\ 9)\ Eco = 0{,}19 Cov, \\ 10)\ Med = 0{,}222 Cov + 0{,}496 Eco + 0{,}001. \end{cases} \tag{4}$$

The assessment of the obtained parameters allows for the conclusion that the increase in the level of vulnerability of the region from the pandemic by 1% corresponds to an increase in the number of beds occupied by patients with COVID-19, the level of morbidity and the number of deaths from this disease by 0.21, 0.22, and 0.23%, respectively. The obtained regression equations show that all three indicators uniformly characterise regional vulnerability to the pandemic. The fourth equation of system (4) indicates that the state of the ecological sector of society is directly proportional to the indicator of the amount of emissions into the environment from mobile sources of pollution with a coefficient of 1. Environmental degradation in the region by 1% corresponds to an increase in carbon dioxide emissions by 0.55 %. The sixth equation shows a direct proportional relationship between the improvement in the state of readiness of medical institutions to receive patients and the increase in the number of contracts for medical care of the population based on medical guarantees. A 1% increase in the quality of medical services corresponds to an increase in the number of anaesthesiologists and the number of beds by 1.1% at the same time. The ninth and tenth equations of system (4) describe the relationship between implicit variables and describe a direct proportional relationship between all the areas considered. The deterioration of the situation with the pandemic by 0.19% follows from a decline in the environmental situation in the region by 1%. In the event of an increase in vulnerability to COVID-19 by 0.22 %, and the environment by 0.5%, the burden on the medical sector would increase by 1%.

Among the found coefficients and free terms of the regression equations of system (4): 18 out of 21 have significant t-statistics ($p<0.05$). To assess the quality of model fitting, the reflector matrix (5) was used, which is the difference between covariance matrices based on empirical data (I) and theoretical (R) of dimensions 8×8, because it can only be constructed for explicit variables:

$$\varepsilon = I - R \tag{5}$$

The reflector matrix value should be contained within [-1;1], Table 3 shows the average absolute real value, not counting the diagonal zero values of 0.21, is close enough to zero and indicates that the model is resilient to scale changes.

Table 3. Reflector matrix – the value of differences between the empirical and theoretical values of the constructed model

	E_Vykydy	E_Diox	M_MedGar	M_Aneste	M_Lizhka	C_lizhka	C_Zahvor	C_Pomerl
E_Vykydy	0.000	-0.134	-0.066	0.534	-0.041	0.305	-0.575	-0.018
E_Diox	-0.034	0.000	-0.312	0.148	-0.039	0.077	0.131	-0.004
M_MedGar	-0.059	-0.761	0.000	0.247	-0.058	0.111	-0.202	-0.007
M_Aneste	0.371	0.443	0.285	0.000	-0.067	-0.263	0.215	-0.026
M_Lizhka	-0.068	-0.162	-0.125	-0.126	-0.000	-0.225	-0.341	0.072
C_lizhka	0.391	0.390	0.209	-0.489	-0.260	0.000	0.613	-0.024
C_Zahvor	-0.345	0.309	-0.197	0.169	-0.170	0.287	-0.000	0.006
C_Pomerl	-0.224	-0.186	0.053	-0.309	0.560	-0.231	0.120	-0.000

Source: developed by the authors

After analysing the final statistical indicators, it is concluded that the constructed model (4) is adequate. The Maximum Residual Cosine indicator is zero, which means that the iterative process converged successfully, and the number of iterations performed is 11. The ICSF Criterion and ICS Criterion tend to zero, which indicates that the model is resistant to multiplication by a constant scale multiplier. The indicator χ^2=44,119 is greater than the corresponding Tabular value of 28.9, with 18 degrees of freedom at the significance level of 0.05. Therefore, this relationship is not random and the results of the model can be considered. The level of $p=0.001<0.05$ and RMS Standardised Residual 0.085<0.1, which also confirms the adequacy of the constructed model. The study also analyses the measures of non-central trends in the constructed model (Table 4), indicating the degree of adequacy of the model based on non-central statistics χ^2 and indicating the lower and upper limits of the confidence interval, as well as a point estimate of the indicator. The non-central distribution parameter, the Stinger-Lind's index, the Macdonald non-centrality index, and the Gamma indices went beyond the norm, which indicates a low quality of fitting this model.

Table 4. Non-central trend indexes for checking the quality of the constructed model

	Lower limit (90%)	Point estimation	Upper limit (90%)
Non-centrality parameter	0.244	0.823	1.724
Stinger-Lind's index	0.116	0.214	0.309
McDonald's non-centrality index	0.422	0.663	0.885
Gamma distribution index	0.699	0.829	0.943
Adjusted gamma distribution index	0.398	0.659	0.885

Source: developed by the authors

Thus, after analysing all the criteria for checking the adequacy of the constructed model (4), the study has come to a general conclusion that despite the insufficient quality of non-centrality indices, the model is resistant to scale changes, has significant coefficients, and is adequate according to the criterion χ^2.

The conducted research theoretically proves that there is a relationship between such spheres of society as ecology and medicine. In order to assess the state of the entire industry – a latent variable, the optimal number of factors was selected that allow assessing all the variability of this implicit indicator. In addition, the study examines the causes of differentiated vulnerability to the effects of the pandemic in different regions of the country. The conducted modelling with structural equations proves that the decentralisation introduced in Ukraine has consequences in the context of a different distribution of funds among the regions, which is reflected in the increase in differentiation of payments to support the environment, medicine and other industries. The authors [2; 4-5] also considered the relationship between the COVID-19 pandemic and the environment, and the authors [3; 7; 10] analysed the medical field. This study confirms and combines the results, because it considers three areas at once as a whole, and not individual indicators. However, the issues of studying the impact of the social sphere, cultural indicators and age distribution of the population on regional vulnerability to the pandemic remained unresolved. Consideration of these issues would allow compiling a rating of areas that require state support, in particular funding, and have an impact on the vulnerability of regions to COVID-19. After all, supporting only one industry would not give one hundred percent effect without comprehensive consideration of any problem. Only a systematic consideration of the problem allows overcoming adversity, using entire state budget to the maximum.

Conclusions

By modelling structural equations, the relationship between the factors of vulnerability of the regions of Ukraine from the COVID-19 pandemic, the environmental state and the state of readiness of the medical system is proved. It is theoretically substantiated that this dependence is direct in nature. If the state of the region's ecology worsens by 1%, the population's vulnerability to the pandemic worsens, in terms of morbidity and mortality by 0.19%. If the burden on the medical sector increases by 1%, there will be a proportional increase in the burden on the environment and vulnerability to COVID-19 by 0.5 and 0.22%, respectively.

The results obtained prove that approaches to choosing strategies to overcome current and future epidemiological waves should be approached comprehensively. Support for one industry does not give 100% results, without support for related areas, which is demonstrated by the results of the study. As an example, with the emergence of the pandemic, the medical sector received significant state financial support, but there was still a significant differentiation in the vulnerability of the regions of Ukraine. This indicates, according to the results of the study, the importance of financing the state of the environment for maintaining public health at the proper level. This would allow making adjustments in advance in the state and regional policy in relation to the medical sphere, ecology to carry out management not only in the event of threats after the fact, but also to plan in advance and prevent any negative impacts – after the event. A systematic review of the relationships between different areas of the state would allow identifying a set of parameters for prioritising initiatives in the context of overcoming the negative manifestations of future epidemiological waves.

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Структурне моделювання взаємозв’язку між вразливістю регіонів України від COVID-19, екологічним станом і чинниками готовності медичної системи

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Анотація. Розподіл областей України на «червону», «помаранчеву», «жовту» та «зелену» зони є наслідками диференційованого регіонального впливу пандемії, викликаної вірусом COVID-19, проте причини такої різної вразливості досі не з’ясовані. Основною метою проведеного дослідження є побудова системи регресійних рівнянь, що містять неявні змінні, що є загальними характеристиками галузей і допомагають проаналізувати взаємозв’язки у складній системі. Методичним інструментарієм проведеного дослідження стали: огляд сучасних наукових тенденцій за допомогою VOSViewerv.1.6.10, метод головних компонентів, який дає змогу відібрати найбільш вагомі чинники та моделювання структурними рівняннями, що відображають взаємозв’язок між трьома сферами діяльності. Об’єктом дослідження обрані 25 регіонів України, оскільки саме вони мають різні рівні вразливості від пандемії та можуть стати зразком для дослідження регіональної диференціації будь-якої країни. У статті представлено результати емпіричного аналізу дослідження структури трьох сфер діяльності країни. Здійснено моделювання структурними рівняннями щодо встановлення взаємозв’язку між чинниками вразливості регіонів України від пандемії COVID-19, екологічним станом і станом готовності медичної системи. Теоретично обґрунтовано, що між досліджуваними сферами: екологічна, медична та епідеміологічна існує прямий зв'язок, та погіршення в одній галузі призводить до погіршення в іншій. Отримані результати доводять, що впливати на диференційований перебіг пандемії можна, але не постфактум. Послідовне збільшення фінансування з державного бюджету сфери охорони здоров’я матиме більший ефект, при достатньому фінансовому забезпеченні охорони навколишнього середовища. До вибору державних стратегій необхідно підходити комплексно, адже вузьке реформування системи, наприклад медичної, не дасть максимального ефекту без інноваційної політики у сфері екології

Ключові слова: пандемія, економетрика, екологія, медицина, метод головних компонентів