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MODELING THE SUSTAINABLE DEVELOPMENT OF THE UKRAINIAN REGIONS BY NEURAL NETWORKS

Abstract. The article is devoted to the issue of modeling sustainable development of regions. In the article, the author notes that the issue of modeling sustainable development of regions has long been engaged in both domestic and foreign scientists. However, this topic is still relevant today. The paper emphasizes the importance of preserving the ecological state of the country in general and at the regional level in particular. It also emphasizes the need for harmonious development of social, economic and environmental spheres. Literary analysis of scientific works in the direction of research also leads the work of researchers and approaches to modeling the sustainable development of regions that were presented several decades later. The author gives a brief overview of the models that have already been proposed by researchers and notes the advantages and disadvantages of these models. Summarizing the analysis of literature research, the paper identifies a number of problems that are still unresolved in modeling sustainable development of regions.

The paper aims to eliminate the existing contradictions in the modeling of sustainable development and proposed an alternative approach to modeling which is based on establishing a reliable relationship between the main indicators of the region in three areas: economic, environmental and social.

In accordance with this goal, the author hypothesized the possibility of using the tool of neural networks in order to form reliable links between indicators of sustainable development and the implementation of further modeling.

Thus, the paper presents arguments in the direction of using neural networks to achieve the goals.

In order to build a neural network, the author formed a system of input and output parameters in three areas: economic, social and environmental. In selecting the factors, the author relied on his previous published study in which a correlation analysis of sustainable development factors was conducted, and the most influential ones were selected. The basis for the training of neural networks were statistical data on the sustainable development of Ukraine from 2004 to 2018.

The construction of three neural networks: economic, social and environmental spheres. Only 70 percent of the sample data was used to train the networks, and the rest was used for testing. As a result, the constructed neural networks showed a high degree of forecast quality and can be further successfully used to model indicators of sustainable development of regions. The constructed neural networks are able to determine the indicators of sustainable development, which are represented by the main macroeconomic indicators of the region, based on a significant number of input parameters. Moreover, this approach will not only model sustainable development, but also determine the extent to which a factor affects it.

The paper notes the prospects for further research which may be further testing of the obtained neural network on specific examples (indicators of development of the regions of Ukraine) in order to model. Also, the resulting neural network can be used as a basis for the optimization problem of finding optimal indicators of regional development.

Keywords**:** sustainable development, regional development, modeling of sustainable development of regions, neural networks, indicators of regional development, ecological sphere of the region, economic sphere of the region, social sphere of the region.

JEL Classification C45, O18, R15

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МОДЕЛЮВАННЯ СТІЙКОГО РОЗВИТКУ УКРАЇНСЬКИХ РЕГІОНІВ ЗАСОБАМИ НЕЙРОННИХ МЕРЕЖ

Анотація. Присвячена питанню моделювання сталого розвитку регіонів. Зазначено, що питанням моделювання сталого розвитку регіонів уже достатньо тривалий час займаються як вітчизняні, так і закордонні науковці. Але ця тема й нині залишається актуальною. Наголошується про важливість збереження екологічного стану країни взагалі та регіонів зокрема, про необхідність гармонійного розвитку соціальної, економічної та екологічної сфер. Літературний аналіз наукових робіт у напрямі дослідження також наводить роботи дослідників і підходи до моделювання сталого розвитку регіонів, які були представлені декілька десятиліть тому. Дано короткий огляд моделей, які вже були запропоновані науковцями і дослідниками, та відзначено переваги і недоліки цих моделей. Підсумовуючи проведений аналіз літературних досліджень, виділено низку проблем, які все ще не є вирішеними при моделюванні сталого розвитку регіонів.

Поставлено за мету усунути наявні протиріччя в моделюванні сталого розвитку і запропонували альтернативний підхід у моделюванні, який базується на встановленні надійного взаємозв'язку між основними показниками діяльності регіону у трьох сферах: економічній, екологічній і соціальній.

Відповідно до поставленої мети висунуто гіпотезу про можливість застосування інструменту нейронних мереж з метою формування надійних зв'язків між показниками сталого розвитку і виконанням подальшого моделювання.

Отже, наведено аргументи щодо використання нейронних мереж для досягнення поставлених цілей.

З метою побудови нейронної мережі сформовано систему вхідних і вихідних параметрів за трьома сферами: економічної, соціальної та екологічної. При виборі факторів ураховано попереднє опубліковане дослідження, у якому було проведено кореляційний аналіз факторів стійкого розвитку та відібрано найбільш впливові. Основою для навчання нейронних мереж послужили статистичні дані стійкого розвитку України з 2004 до 2018 року.

Виконано побудову трьох нейронних мереж: економічної, соціальної та екологічних сфер. Для навчання мереж використовувалось лише 70 відсотків даних з вибірки, інші були використані для тестування. У результаті побудовані нейроні мережі показали високу ступінь якості прогнозу і можуть бути надалі успішно використані для моделювання показників сталого розвитку регіонів. Побудовані нейроні мережі здатні визначати показники стійкого розвитку, які представлені основними макроекономічними показниками регіону, на основі значної кількості вхідних параметрів. Причому такий підхід дозволить не тільки моделювати сталий розвиток, а й визначати, якою мірою той чи інший фактор на нього впливає.

Відзначено перспективи подальших досліджень, якими може стати подальше тестування отриманої нейронної мережі на конкретних прикладах (показниках розвитку регіонів України) з метою моделювання. Також отримана нейрона мережа може бути покладена в основи оптимізаційної задачі знаходження оптимальних показників розвитку регіонів.

***Ключові слова*:** стійкий розвиток, регіональний розвиток, моделювання сталого розвиту регіонів, нейронні мережі, індикатори розвитку регіону, екологічна сфера регіону, економічна сфера регіону, соціальна сфера регіону.

Формул: 2; рис.: 2; табл.: 1; бібл.: 18.

Introduction. Post-industrial society is currently «working at the limit» of its biological capabilities to ensure a comfortable living environment. The reason for this is the limited natural resources available to mankind, as well as their non-reproducibility (or slow reproducibility). At the same time, man-made pressure on nature is growing exponentially every year. Human impact on nature has become particularly significant, virtually uncontrolled and in many cases unpredictable. It becomes clear that it is no longer possible to solve environmental problems only by developing new and implementing existing environmentally friendly and resource-saving technologies.

Countries with economies in transition and Ukraine, including, as never before, urgently need new tools and approaches to the formation of regional policy on the basis of sustainable development in order to ensure the harmonious development of all spheres: social, economic, industrial, business, environmental, etc.

In the methodological aspect of the study, the complex problem excludes any intuitive approaches and requires the use of modern methods of systems analysis and modeling to represent these interactions in mathematical models, which are provided with an appropriate information base.

Literature Review. A large number of scientific works are devoted to the use of methods of mathematical modeling in the formation of the policy of sustainable development of regions. The first work on the model of global development was published in 1970 by J. Forrester. When building the model, formalized models of nonlinear dynamic processes were used. The simulation results showed that if current development trends persist, humanity should expect an economic, environmental and social crisis. The model developed by J. Forrester, which, in its time, drew public attention to world problems, was also the impetus for further research in the field of modeling, namely the emergence of a new direction — global modeling [1; 2].

Also, the model of D. Pierce and K. Turner became widespread. The model reflects the inverse relationships in ecological and economic systems. One of the first models, which was devoted to the study of the relationship between the economy and the environment, is the model of intersectoral balance proposed by V.V. Leontiev and D. Ford. The intersectoral balance in the model is presented as the interaction of flows of goods and services of individual sectors of the economy. In the balance method, the laws of equilibrium between raw materials, ecology, etc. must be observed. The idea of a model of intersectoral balance makes it possible to establish relationships between industries in the region in the process of its activities. However, the model of intersectoral balance is more focused on production and economic activity. The processes of nature in it affected only the cost of compensation for pollution [3; 4].

Since the advent of the intersectoral balance model, it has been significantly modernized, particularly at the regional level.

The model presented in [5] also aims to establish links between the natural environment and the region's economy. As a criterion for optimizing this model, the minimization of the total reduced costs of production along with the minimization of costs for environmental measures. Among the shortcomings of the model is that the model does not take into account the social component of regional development, and as for the environmental, it takes into account only one indicator of pollution.

Among the Ukrainian researches, I would like to note the works of I. M. Lyashenko, which made a significant contribution to the development of socio-ecological and economic modeling. Based on the simulation results, the optimization of the branch structure of Ukraine taking into account the ecological component was performed and the ecological and economic model of optimal development of separate territories was developed [3; 6; 7].

But, despite the variety of strategies, they all, in our opinion, have a number of disadvantages:

– Assessment of the sustainability of regional development is performed only on the basis of certain indicators, which, in turn, are assessed on the basis of statistical data and compared with the boundary conditions. However, this approach only gives a clear picture of the current situation. It does not allow modeling the development of the region by establishing cause-and-effect relationships and analyzing possible scenarios in the implementation of certain strategic goals, and therefore is not effective in managing regional development and regional policy.

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– The variety of approaches to assessing the sustainability of regions, the presence of different groups of criteria, the presence of different levels of marginal criteria of sustainable development leads to the fact that each region independently forms assessments of sustainability, which are essentially inconsistent in different regions. With approximately the same indicators of development, one region may consider itself as a region that meets the conditions of sustainable development, and another — no. This means that at the national level it is not possible to assess the sustainability of development of both regions and the state in general. The only solution in this direction, in our opinion, should be the centralized development of methods for assessing the sustainable development of regions with the establishment of a single list of indicators and boundary conditions for them. The new methodology should not only assess the current state of the region's development in accordance with the principles of sustainability, but also take into account the causal links between the region's performance indicators in order to develop strategic goals and make effective management decisions based on sustainable development.

Methodology and research methods. There is an objective need to assess the degree of instability of the environment, as well as to develop approaches to its analysis. In this aspect, the choice of optimal selection of parameters, which will determine the relevance of the goals of sustainability, is one of the topical issues. In this regard, the primary task is to analyze existing system parameters and identify problems associated with their application.

The authors have already carried out a correlation analysis of the parameters proposed by the World Data Center for Geoinformatics and Sustainable Development [8] in the collection «Ukraine in Sustainable Development Indicators 2013» [9]. This analysis has once again confirmed the previous thesis of the weak structuration of the system and the nonlinearity by its nature. Statistical methods are well developed only for one-dimensional random variables. If you consider several interrelated factors, then it will have to turn to the construction of a multidimensional statistical model. However, such models either foresee the distribution of Gaussian observations (which is not performed in practice) or are not theoretically substantiated. Thus, there is a need to use an improved mathematical apparatus, which could be neural networks.

The neural network is an analogue of the human brain in an artificial form. The main components of the network are neurons capable of processing input information on the principle of the human brain. Neurons, in turn, are grouped into layers and make connections both within their layer and with other layers, of which there may be many. The input signal is received by the neurons of the first layer, then information is processed and data is transmitted to the neurons of the second layer, and so on. At the output of the neuron get the state of its activity.

Consider the main features of neural networks that determine the choice of this tool to solve problems:

1. Neural networks are able to perform modeling of an economic system or process that is influenced by a large number of factors.
2. Due to its powerful predictive properties, the use of neural networks is appropriate in conditions of uncertainty.
3. Neural networks are universal in nature. They do not depend on the characteristics of the input data, which may have completely different units of measurement, do not require the linearity of the objective functions.
4. Neural networks do not require data. They are able to model dependencies both in the case of very large and in the case of very small amounts of data. And this is a significant advantage of neural networks over other known statistical methods.
5. When solving problems with the use of neural networks, the process of finding solutions is significantly accelerated due to the fact that the search for a solution is performed by the simultaneous processing of data by all neurons.
6. Neural networks are a very powerful mathematical apparatus for solving modeling problems because they are nonlinear. Consequently, they are able to establish relationships between data groups in a complex formalization of processes. It is appropriate to use a neural network when the nature of the connection between input and output is not known, it is enough to assume the

existence of this connection, the nature of the dependence will be revealed in the process of learning the network.

In general, neural networks have proven themselves very well in solving problems of forecasting, classification, encoding and decoding of information in economic systems in general and in risk management of any system [10].

Among researchers who have used neural networks to model sustainable development can be identified work [11]. In this paper, the author proposes the use of only three sub-indices, which can be retrieved from three global reports. Also, of note is the work of [12], in which the author uses a neural network to forecast the development of socio-economic systems. The study focuses on the fact that well-known forecasting methods such as the regression and exponential model, the Holt-Winters method are based on extrapolation, which is an extension of a tendency observed in the past and present to the future. However, socio-economic systems are not linear and not stable in nature, and therefore the use of such methods is not very effective. The study proposes the use of neural networks for predicting socio-economic systems.

Therefore, provided the above, it can be concluded that the neural network meets all the requirements set in this work to model the parameters of sustainable development of the regions.

For the first time a system of factors and a metric was proposed for measuring the processes of sustainable development of regions of Ukraine in the first collection of the World Data Center for Geoinformatics and Sustainable Development (hereinafter referred to as WDC — Ukraine) [8] under the KPI «Analysis of Sustainable Development: Global and Regional Contexts» in 2009. In the latest collection «Ukraine in Sustainable Development Indicators 2013» [9], they propose an approach to the analysis of Sustainable Development (SD), which absorbed the experience of predecessors, the work of experts from three areas: economic, environmental and social.

The paper aims to eliminate the existing contradictions in the modeling of sustainable development and proposed an alternative approach to modeling which is based on establishing a reliable relationship between the main indicators of the region in three areas: economic, environmental and social.

Research results. By collecting data from the State Statistics Service of Ukraine, profile ministries, and non-governmental organizations, WDC — Ukraine created a database with free access [9], which used in this study. The analysis used data from the WDC — Ukraine, namely indicators of 17 parameters from 22 regions in the period from 2004 to 2018, that is 286 observations.

In addition to the parameters proposed by the relevant experts, indicators and policy categories were still introduced threats, which undermine the constancy of the regions. These threats were calculated according to the methods proposed by the experts, which published in the collection mentioned above of WDCs. Relevant threats will be highly appropriate to use as target functions or output parameters for the analysis and development of sustainable development policies.

As a result of the previous correlation analysis, the system of input and output parameters was formed [13]. The factors were established taking into account the research of WDC and other native scientists [14—18].

Consequently, in the framework of this study, the input and output parameters of the sustainable development of the *economic sphere* are:

• *inputs:* Economically active population, Share of food and non-alcoholic beverages on average per month per household, Number of active enterprises, Capital investments, Volume of imports of goods and services, Volume of scientific and technical works performed by the own forces of scientific organizations, Volume of retail trade turnover, Volume of realized innovative products, Volume of realized services, Volume of sold industrial products (goods, services), The volume of expenditures in the areas of innovation activity, The need for enterprises in the workers, Agricultural products.

• *outputs*: Gross Regional Product (VRP), Unemployment Rate (BN), Lowering the Welfare of the Population (DNO).

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The *social sphere* describes a model with the following parameters:

• *inputs* Housing Level, Number of HIV-infected, Level of trust in NGOs, Total number of victims of crime, Children's coverage by pre-school educational institutions by region, Household's level of computer ownership, Level of Freedom from Corruption (Corruption Perceptions Index), Trust in the Church, Distribution of Newspapers by Types and Regions, Economically Active Population, Education Level, Mortality of the Population by the Causes of Death, Human's health and safety indicator, The share of food and non-alcoholic beverages on average per month per household, Gross regional product per capita, Share of people with incomes below the subsistence level, Satisfaction with life, Inequality of distribution of material goods, Level of trust in the media, Number of religious organizations, Level of trust in state institutions: Local authorities, Indicator of the health of the population by doctors of all specialties, Readiness for protests, Population provision by objects of physical culture and sports, Number of employed population in the field of public administration);

• *outputs* (Life expectancy (LIFE_EXP), Crime level (CRIME), Corruption level (CORR_PER), Level of Social Inequality (CIR), Mortality level (MORT).

For the ecological system it is the following parameters:

• inputs (Emissions of pollutants in the ambient air from stationary sources of pollution and motor vehicles per capita, Population share in the zone of possible chemical contamination, Formation of waste of I—III classes of hazard per square kilometer of territory, Formation of waste of IV classes of hazard per square kilometer of territory, Ecological stability of the territory, Radiological state of the territory and chemical danger, Contamination of the territory with strontium-90. The use of fresh water in relation to the GRP, The share of reversible and consecutive (re) used water in the total volume of water use for production needs, Presence of waste of I—III classes of hazard per square kilometer of territory, Presence of waste of class IV hazard per square kilometer of territory, Waste management, Share of freshwater from natural water objects in renewable water resources of the region, Discharge of contaminated waste water into surface water bodies;

• *outputs* (Carbon Dioxide Density Index CCH1 reflects Impact on Climate Change, Technical Disaster THS).

Using the above parameters, it is the opportunity to construct a model that describes the economic, social and environmental spheres. The most widely used algorithms that allow us to investigate the nonlinear relationship between parameters are the methods of machine learning. The Nobel Prize winner 2017 and behavioral economist Richard Tyler in their articles noted that eventually, the entire economy would become behavioral. He argued his thesis that it now needs the development of economics through an extensive array of available information and this will lead to an increase in R2. Today, the methods which simulating the activity of the human brain give the most accurate prediction, namely, neural networks. Currently, other methods of machine learning are widely used, namely, an extreme gradient descent, a random forest method. It is chosen the method of neural networks, as it is more grounded for use in the study of indirect ligaments, in particular in the economy and social spheres. There is also the advantage of this method in the ability to better interpret the result.

It is necessary to construct a model employing neural networks taking into account all the parameters mentioned above. When constructing the model, it is eliminated the effects of steady effects because of the complexity of their interpretation.

The operation of such a network is described by the formula:

$$OUT = sigm(\lambda_2 \sum_{j=1}^{4}(sigm(\lambda_1 \sum_{i=1}^{11} x_i w_{ij})w_j), \tag{1}$$

where w_{ij} — the weighting factor of the i-th input of the neuron number j in the first layer;

w_{ij} — the weighting factor of the j-th input of the neuron of the second layer;

$OUT_к$ — neural network output signal-standardized performance indicators of the region: economic, social, environmental.

λ_1 та λ_2 — the coefficients of steepness of the sigmoid of the first and second layers, λ_1 and λ_2 was approximately 0,5.

Before constructing the model, it was decided to pre-normalize them to have the value of all parameters in the range [0,1] by the formula:

$$x = \frac{x_i - \bar{x}}{x_{max} - x_{min}}. \quad (2)$$

The classical approach for the analysis of the different parameters in the various spheres on the regional level is difference-in-difference, which makes possible to avoid endogeneity regarding the regionally based specifics. So, this normalization procedure practically separates some region's specifics.

To check the model's performance, it is splited all the data into two sets of training and test (70% and 30%). To get two independent samples, it is randomly divided them and compute the *t*-criterion for dependent samples (pairwise comparison between group levels with patches for multiple testing). For this criterion, the calculated *p*-value was less than 0.10 when breaking data for all three spheres.

The activation function was chosen as sigmoid since data was normalized beforehand. The network learning algorithm was chosen by RProp, because of its higher efficiency compared to the classic Backprop. This efficiency is to use only partial derivatives for the weighting coefficients. Due to this, the accuracy of the forecast remained at the same level as the classic algorithm, and the calculation speed increased several times.

The architecture of the neural network used in the simulation of all three spheres has the following specifications: step = 0.01, the number of neurons = 4, error function is the sum of mean square errors. It is determined the average model quality using a 100-fold calculation of the model for each sphere.

For each calculation of the model, the root mean square error (RMSE) and the correlation between the test and the forecast are calculated. The results of the models are shown in *Table*.

Table

Results of models work

Sphere	**Economic**			**Social**					**Ecological**	
Parameter	VRP	DNO	BN	CIR	CORR_PER	CRIME	LIFE_EXP	MORT	CCH1	THS
Correlation	0,90	0,91	0,50	0,70	0,90	0,77	0,98	0,94	0,75	0,17
RMSE	0,05	0,02	0,06	0,04	0,03	0,02	0,01	0,02	0,01	0,10
Regression	0,9	0,12	0,1	0,1	0,2	0,15	0,18	0,09	0,12	0,3

In order to assess the effectiveness of neural networks, a prediction was also performed using regression analysis. A nonlinear regression equation was constructed to establish the relationship between the selected input parameters and the output parameters. The error that was obtained as a result of building a regression model is presented in *Table*. Thus, we can conclude that to achieve the goals of this study, neural networks are a more effective mathematical tool.

Fig. 1 shows the architecture of the constructed neural network on the example of the economic sphere. The input of the network, which is reflected on the right, receives signals about the input parameters of economic development of regions, then, in the hidden layer is learning the network and the values of weights (displayed on the lines connecting neurons from the first to the last layer). The final stage of network training is to obtain the values of the initial parameters of the network. The output parameters of the network are the main macroeconomic indicators of regional development, which are represented by Gross Regional Product (VRP), Unemployment Rate (BN), Lowering the Welfare of the Population (DNO).

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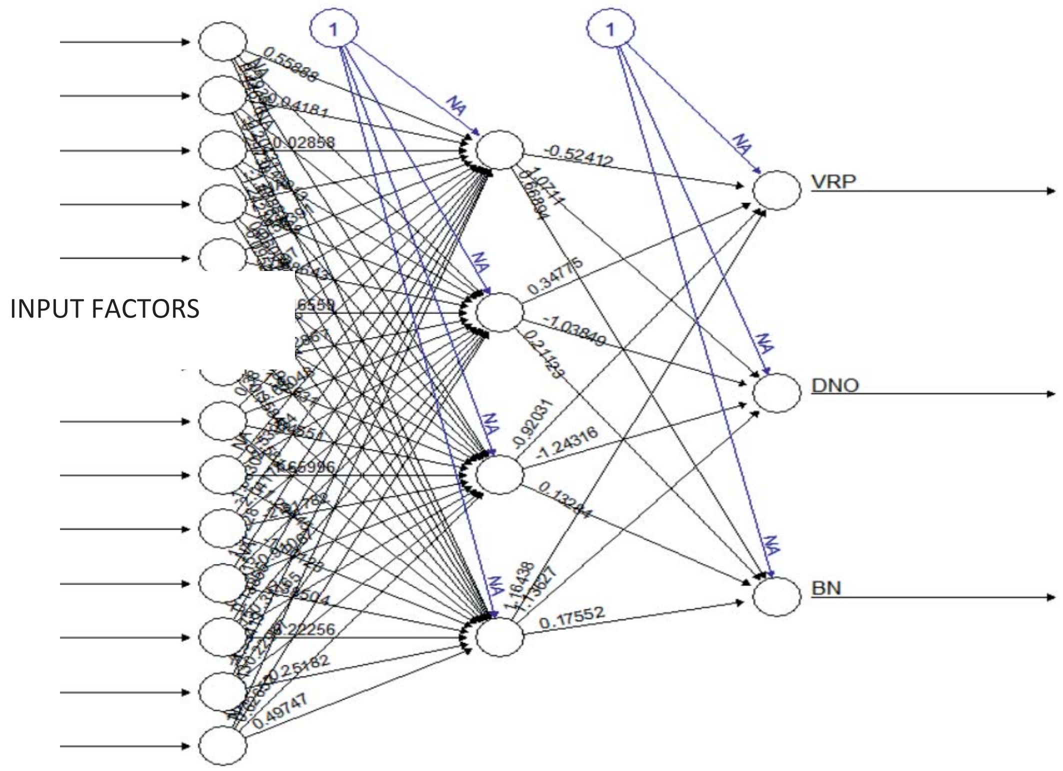

Fig. 1. **Visualization of the neural network of the economic sphere**

The architecture of neural networks for the environmental and social spheres have a similar architecture, so in this work they are not presented separately.

The most successful application of the neural network took place in the modeling of the social sphere. The reason for this is the relatively large number of parameters. The parameters that describe «Gross Regional Product» and «Existing Household Income» are poorly described by «Unemployment Rate». The results of the modeling of the environmental sphere indicate that the selected parameters somewhat explain the climate variability, but the causes of human-made hazards are described by parameters that are not part of our data set.

As can be seen from *Fig. 2*, the scatter of points is not significant. This position once again clearly confirms the adequacy of the developed economic and mathematical model of neural networks to make a qualitative forecast in order to model sustainable development. When modeling a more extended period using the first, second and third lags, the quality of the forecast almost did not decrease.

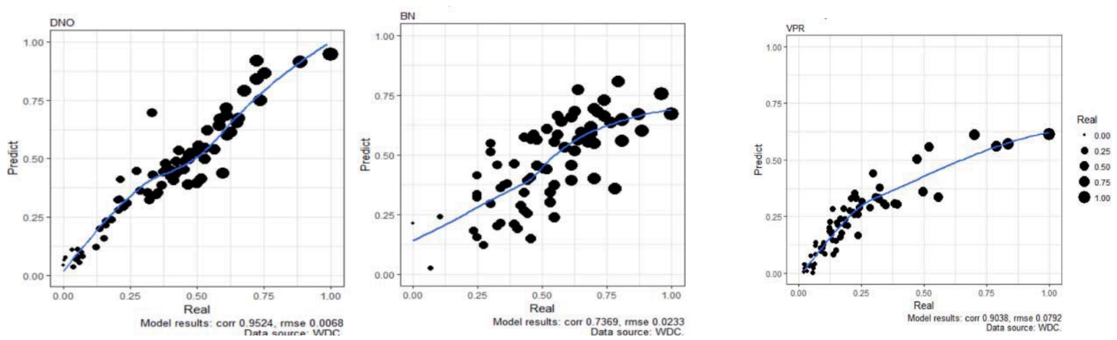

Fig. 2. **Visualization of the result of the model of the economic sphere**

The next step is to predict the output parameters for 2018, 2017—2018 and 2016—2018 using data for the period 2004—2017, 2004—2016 and 2004—2015 respectively. This variability is necessary in order to assess how the network works on different data samples.

For comparison, the average network error at the training stage was 0.034. At the testing stage using data for the period (2004—2017) — 0,059; (2004 — 2016) — 0,024; and (2004—2015) — 0,032 respectively.

It indicates the suitability of such a model for the forecast in the short run. For a long-term forecast, additional data is needed.

Conclusions. In this study hypothesized the use of neural networks as an effective mathematical method to perform modeling of sustainable development of the regions of Ukraine. In order to confirm the hypothesis in the study, the construction of neural networks in the economic, social and environmental spheres was performed. A network with the inverse error type was selected and a sigmoid was selected as the activation function. To build the model in the work, a number of input and output data from 2004 to 2018 were selected. After training the neural network and its further testing, a high efficiency of the predictive model was obtained. Therefore, it is assumed that neural networks are an effective tool in building models of sustainable development of regions. Further collection of statistics for new periods will allow to complete the constructed neural network in order to improve the accuracy of the forecast in the future.

The obtained model allows to perform with high accuracy forecasting of indicators of development of the region taking into account a large number of factors. In addition, it can be analyzed how this or that factor affects the sustainable development of the region and on the basis of the obtained data to develop economic, social and environmental measures to improve the development of regions in general.

Also, the obtained neural network solved all the problematic aspects in the modeling of sustainable development that were formed at the beginning of this study.

Further research in this direction is seen in the construction of an optimized neural network optimization model for the optimization of sustainable development of the regions.

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