Artificial Intelligence in Forecasting Demographic Processes

Stepan Mezhov and Maxim Krayushkin
Altai State University, Lenin Str. 61, 656049 Barnaul, Russia
megoff@mail.ru, kramaks-97@mail.ru

Keywords: Forecasting, Artificial Intelligence Models, Artificial Neural Networks, Model Error, Population Size, One-Year Old.

Abstract: At the moment, there are no universal tools for forecasting indicators of socio-economic development in general and demographic in particular. However, the amount of budget allocations that are directed to solving personnel issues, creating social facilities and implementing other activities significant for economic, social and infrastructural development, development vectors depend on the forecast of demographic indicators by one-year-olds. In this article, a meaningful analysis is carried out an analysis of the researchers' work, based on the results of which it is determined that artificial intelligence models, in particular the most adaptive neural networks, are almost not used in predicting demographic indicators, forecasts based on models of artificial neural networks for all ages or by age groups, have almost no significance from the point of view of managing socio-economic development. The result of the research is a neural network methodological approach, methodology and tools for forecasting demographic processes for one-year-olds. The developed methodological approach to forecasting and tools are universal in the field of forecasting socio-economic indicators. In addition, the results described in the article can be used in other research in the field of forecasting, planning of any indicators.

1 INTRODUCTION

The amount of budget allocations that are directed to solving personnel issues, creating social facilities and implementing other activities significant for economic, social and infrastructural development, development vectors depend on the forecast of demographic indicators by one-year-olds.

At the moment, there are no universal tools for forecasting indicators of socio-economic development in general and demographic in particular.

A meaningful analysis of the researchers' work has shown that the most common methodological approaches to demographic forecasting are:

- Time series modeling.
- Building regression models.

This thesis is determined based on a constructive analysis of the work of more than 50 researchers.

The problems of constructing demographic forecasts as an essential element of the socio-economic development planning system have been sufficiently worked out in terms of tools and modeling. Conceptual approaches to the construction of demographic forecasts were developed by such researchers as Graunt J. [1], Malthus T. [2], Pearl R. [3], Reed L.[3], Welton P. [4], Vishnevsky A. G. [5] and others. A significant contribution to the development of tools for building computer models of demographic processes has been made: Meadows D. [6], Simon G.A. [7], Forrester J. [8, 9], Tsybatov, V.A. [10] and others. In their work, the above-mentioned researchers also focused on the possibility of predicting demographic processes using regression models and time series models. However, the main disadvantage of these models is their weak adaptability to changes in the socio-economic situation, which negatively affects the accuracy.

A constructive analysis of studies, including the latest ones from 2023-2024, in which models of artificial neural networks were used to build a forecast of demographic indicators, showed that forecasts using neural networks are built either for all ages or for individual age groups. In turn, such neural network forecasts have almost no value in managing socio-economic development [14, 15, 24, 25]. Only demographic forecasts based on one-year ages have significant value in this process.

In turn, the scientific problem can be determined as follows: the use of subjective, non-adaptive methodological approaches to forecasting indicators of socio-economic development leads to a high forecast error and, as a result, ineffective planning of development. This has a negative impact on economic development and the standard of living of the population.

Therefore, the purpose of the study is to develop theoretical and methodological provisions and tools based on them to improve the planning system for socio-economic development in the context of forecasting demographic processes by one-year-olds based on artificial intelligence.

2 MATERIALS AND METHODS

When developing tools for the formation of an information base, autocorrelation and cluster analysis are used, and artificial neural networks are used for modeling.

When building neural networks in the framework of the study, neural network training was chosen as a paradigm: with a teacher; training rule – error correction; architecture – a multilayer neural network; learning algorithm (optimizer) – BFGS.

When using training models of artificial neural networks with a teacher, when correcting an error, the parameters of the neural network are determined in such a way that the actual data are as close as possible to the values obtained from the model, that is, so that the model error is minimal (it is on the test sample). To solve the forecasting problem, it is important that the accuracy of the model be as high as possible, because the effectiveness of socio-economic development management depends on the accuracy of the forecast. Therefore, neural network training with a teacher and the error correction training rule were chosen as the paradigm.

To solve the forecasting problem, only multi-layered neural networks are needed. After all, when taking into account a large number of parameters, the probability of increasing the accuracy of modeling increases.

The BFGS algorithm was chosen as the optimizer because it is one of the most effective ways of optimization. Numerous publications on the effectiveness of using this algorithm to solve complex problems not only in forecasting, the use of this algorithm in modern neural network simulation systems prove the expediency of its application in the framework of the study [12].

The structure of an artificial neuron can be represented as follows (Figure 1).

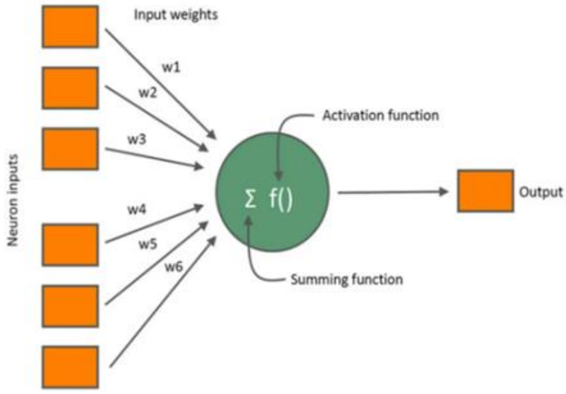

Figure 1: The structure of an artificial neuron.

The scheme of operation of the BFGS algorithm is shown in Figure 2.

Given starting point x_0, convergence tolerance $\epsilon > 0$,
inverse Hessian approximation H_0;
$k \leftarrow 0$;
while $\|\nabla f_k\| > \epsilon$;
Compute search direction

$$p_k = -H_k \nabla f_k;$$

Set $x_{k+1} = x_k + \alpha_k p_k$ where α_k is computed from a line search procedure to satisfy the Wolfe conditions
Define $s_k = x_{k+1} - x_k$ and $y_k = \nabla f_{k+1} - \nabla f_k$;
Compute H_{k+1}
$k \leftarrow k + 1$;
end (while)

Figure 2: Diagram of the BFGS algorithm.

Meaningfully, the algorithm works as follows: at the first iteration, the initial weighting coefficients of the connections in the neural network are determined. In the following iterations, the weight coefficients change until the error value on the test sample becomes minimal [12].

When forming the information base, building neural network models, and forecasting based on them, the STATISTICA 13 version software package.

3 RESULTS

Modern neural network models are much more accurate than time series models and regression models, they have a wider degree of applicability and they are more adaptive. Using specialized software products, they can be built by a specialist without having in-depth knowledge of neural network modeling [13].

Accordingly, in order to increase the accuracy of forecasting demographic processes by one-year-olds, a methodological approach based on the construction of artificial intelligence models, namely artificial neural networks, is proposed.

The characteristics of the neural network approach to demographic forecasting by one-year age proposed by the authors of the article are:

- Building models that conceptually work in a similar way as an expert who develops a forecast.
- Using only adaptive algorithms for building neural network models.

The authors of the article have developed a methodology for constructing a demographic forecast, it is presented in Figure 3.

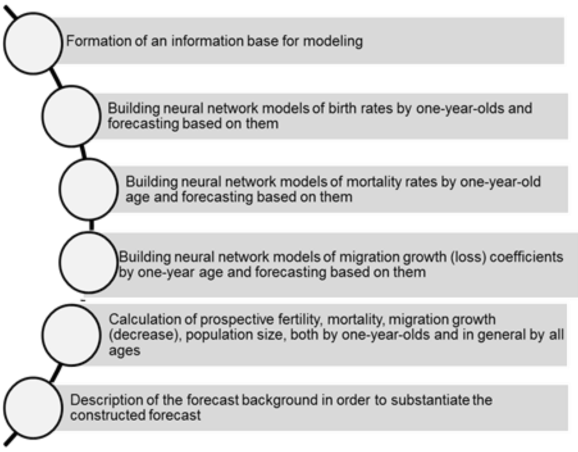

Figure 3: Methodology for constructing a demographic forecast.

Let's consider the developed methodology (Figure 3) in detail.

At the first stage, retrospective information is collected about:

- Age - related birth rates by one- year- olds.
- Age-related mortality rates by one-year age, both among men and women.
- The coefficients of migration growth (decrease) by one-year age, both among men and women.
- The population of each age as of January 1, both among men and women.
- Factors that significantly affect the demographic dynamics.

To collect information, you can use open [11].

Further, for the purpose of modeling, it is necessary to process the data in the appropriate way, that is, to divide it into representative groups. To do this, it is necessary to conduct a cluster analysis. First, it is necessary to determine the optimal number of clusters using the tree clustering method [16].

After that, it is necessary to conduct a cluster analysis using the method, for example, "k-means".

After the data is properly collected and processed, you can proceed to the next steps related to building models and forecasting directly. At subsequent stages, models of fertility rates, mortality, migration growth (loss) by one-year-olds and forecasts based on them are being built. It is already advisable to use artificial neural networks here.

In general, the procedure for building an artificial neural network can be represented as the following steps:

- Choosing a paradigm.
- Selection of the training rule.
- The choice of neural network architecture.
- Choosing the algorithm for building a neural network.
- Selection of the criterion for stopping learning.

Based on a meaningful analysis of the work of researchers in the field of neural network modeling, it was revealed that to solve the problem of forecasting, including demographic processes by one–year–olds, when building neural networks in the framework of the study, neural network training was chosen as a paradigm: with a teacher; training rule – error correction; architecture – a multilayer neural network; learning algorithm (optimizer) – BFGS [12, 17-22].

At the last stage, the stop criterion is selected. It is usually understood as achieving the minimum error value in the test sample.

Based on the results of a comparative analysis of packages, systems and technologies in the field of network neurosimulation in forecasting tasks (STATISTICA, Matlab, Loginom and others), it follows that the most suitable software package is STATISTICA due to its advantages (it is free software, it is possible to analyze and visualize big data, there are packages of statistical analysis, access rights management, predictive analytics, it is possible to download the program code of the model in different programming languages) and ease of implementation for a user who does not have high qualifications in the field of neural network modeling and forecasting [23].

At the penultimate stage of the methodology, the following is carried out:

- Calculation of the number of births by age of one year. The calculation of the number of births for each age is carried out by multiplying the average annual value of the population of the corresponding age in the prospectus period by the corresponding forecast value of the fertility rate.
- Calculation of the number of deaths by age of one year. The calculation of the number of deaths for each age is carried out by multiplying the average annual value of the population of the corresponding age in the prospectus period by the corresponding forecast value of the mortality rate.
- Calculation of migration growth (loss) by one-year age. The calculation of the number of migration growth (loss) for each age is carried out by multiplying the average annual value of the population of the corresponding age in the prospectus period by the corresponding forecast value of the migration growth coefficient (loss).
- Calculation of the population for each age. The calculation of the population of the corresponding age is carried out as follows: from the value of the population of the corresponding age of the previous year, the number of deaths and the number of retirees in the current year are subtracted. However, if there is a migration increase rather than a decrease, then the number of arrivals in the current year is added to the population of the corresponding age of the previous year, minus the number of deaths. The number of newborns is equal to the projected birth rate.

At the final stage of the methodology, a description of the forecast background is carried out in order to substantiate the constructed forecast within the framework of planning socio-economic development.

Using the estimated values of factors that significantly affect demographic processes, the justification of the forecast calculations is carried out. The description of the forecast background is carried out both for the forecast of fertility, and for mortality and migration processes. The predicted value of the demographic variable and the factors influencing it is taken. Then the description of the change in the variable from the corresponding changes in the factors is carried out.

In addition, a description of the forecast background is carried out for the total number and population size by one-year age, depending on changes in fertility, mortality and migration.

Then, based on the methodology developed within the framework of the study (Figure 3), models of artificial neural networks and a forecast based on them were built.

At the first stage, an information base was formed. For this purpose, statistical data were collected on the rates of fertility, mortality, and migration growth (loss) by one-year age from 2012 to 2022. Then an autocorrelation analysis was carried out, the results of which revealed that it is advisable to build models using data from 2017 to 2022. After that, a cluster analysis was performed using tree clustering and "k-means" methods to determine the data arrays for further modeling.

At the second stage, complexes of predictive models of the birth rate by one-year age were built for the corresponding clusters.

When building neural networks in the framework of the study, neural network training was chosen as a paradigm: with a teacher; training rule – error correction; architecture – a multilayer neural network; learning algorithm (optimizer) – BFGS.

When forming the information base, building neural network models, and forecasting based on them, the STATISTICA 13 version software package was used due to its advantages mentioned earlier.

The absolute verification of the constructed models is shown in Figures 4, 5.

Figures 4, 5 show the actual data of the fertility rate by one-year age and obtained using the constructed neural network model. The value of the average absolute error in the percentage of models (MAPE) on training data is less than 2%, on test data – 2-2.5%, retrogression – 3-3.5%. Neural networks have 2 hidden layers of 7 neurons in each of them.

The graph of the neural network of the fertility rate is shown in Figure 6.

The constructed neural network models have 7 neurons in 2 hidden layers. The activation function of neurons is a sigmoid.

The weight coefficients are shown in Table 1.

Similarly, the construction and analysis of the accuracy of models for 2, 3, 4 clusters were carried out.

At the third and fourth stages, neural network models were built in a similar way for the corresponding clusters to predict the mortality rate for men and women, as well as the coefficient of migration growth (loss) for men and women.

All built models, including those for verification based on data from 2022, are quite accurate, according to some models the accuracy reaches 99,5 percent.

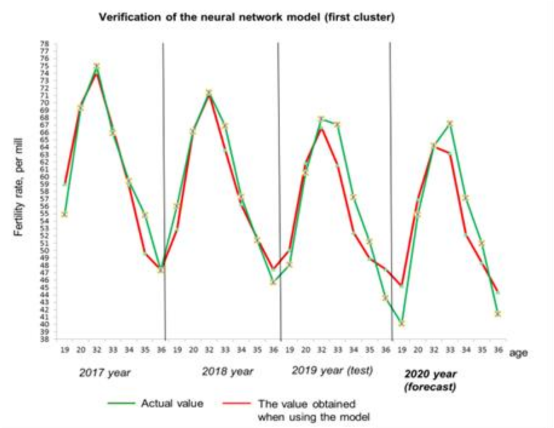

Figure 4: Absolute verification of the neural network for the first cluster (retrospective forecast for 2020).

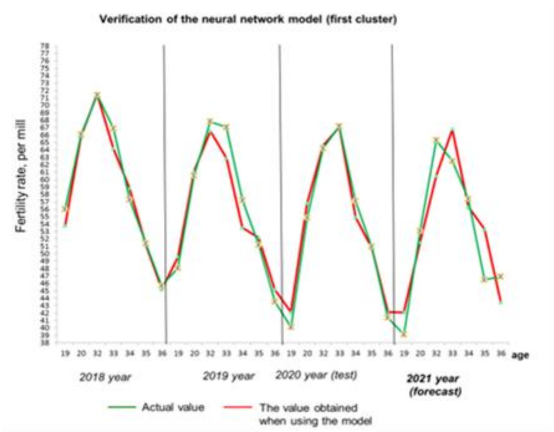

Figure 5: Absolute verification of the neural network for the first cluster (retrospective forecast for 2021).

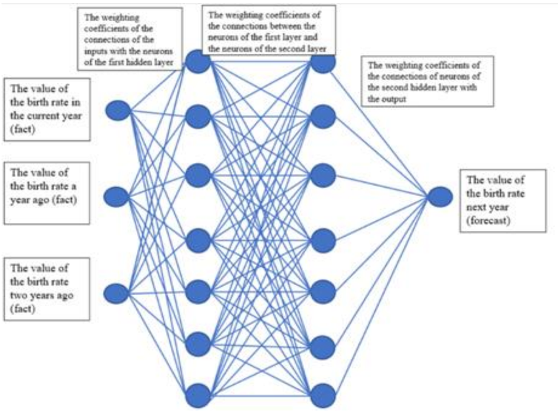

Figure 6: The graph of the neural network of the fertility rate.

Table 1: Weight coefficients.

The weighting coefficients of the connections of the inputs with the neurons of the first hidden layer	The weighting coefficients of the connections between the neurons of the first layer and the neurons of the second layer	The weighting coefficients of the connections of neurons of the second hidden layer with the output
-0,126	0,66	0,132
-0,232	-0,306	-0,576
-0,148	0,372	0,101
-0,47	-0,189	0,511
-0,007	0,651	-0,54
-0,014	0,64	0,415
0,06	0,125	0,136
0,056	-0,013	-
0,096	0,6	-
0,12	0,74	-
0,2	-0,128	-
0,45	0,504	-
-0,05	-0,144	-
-0,165	-0,03	-
0,4	0,008	-
-0,13	-0,08	-
-0,546	-0,042	-
0,198	0,155	-
0,013	-0,044	-
0,232	-0,26	-
-0,104	-0,035	-
-	0,33	-
-	-0,006	-
-	-0,002	-
-	-0,09	-
-	-0,029	-
-	0,132	-
-	-0,06	-
-	0,007	-
-	0,008	-
-	0,008	-
-	0,008	-
-	0,03	-
-	0,052	-
-	0,04	-
-	0,07	-
-	-0,06	-
-	0,01	-
-	-0,015	-
-	0,011	-
-	-0,042	-
-	0,01	-
-	-0,222	-
-	0,033	-
-	-0,018	-
-	-0,168	-
-	0,06	-
-	-0,028	-
-	0,032	-

At the fifth stage, a population forecast was built and its verification was carried out.

The population forecast is shown in Figures 7, 8.

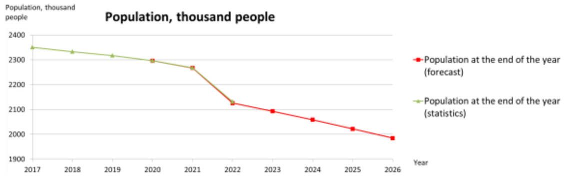

Figure 7: Population forecast.

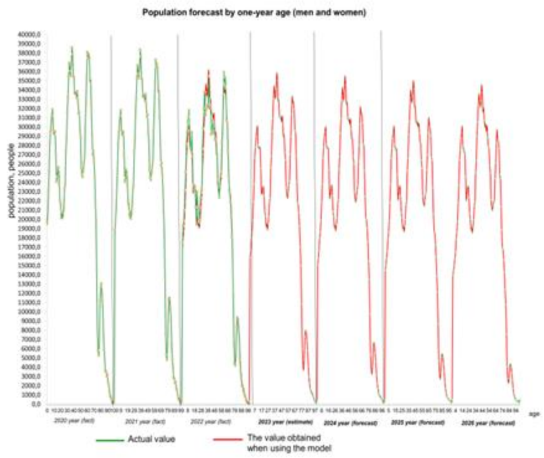

Figure 8: Population forecast (by one-year age).

The use of a neural network approach to forecasting demographic processes by one-year-olds has led to an increase in its accuracy, which will entail increased opportunities to solve socio-economic problems and the need to adjust development plans.

4 CONCLUSIONS

The effectiveness of socio-economic development planning depends on the forecast of demographic processes by one-year age.

During the analysis of the researchers' work, it was revealed that the most adaptive models of artificial neural networks are practically not used in predicting demographic processes.

Therefore, a methodological approach, methodology and tools have been developed for predicting demographic processes by one-year-olds in based on artificial neural network models.

Based on the results of the analysis of the accuracy of the constructed models, it was found that their use is advisable in the process of planning of socio-economic development.

REFERENCES

[1] J. Graunt, "Natural and political observations listed in the attached table of contents and made on the basis of bulletins on mortality. In relation to governance, religion, trade, growth, air, diseases and other changes of the named city. The work of John Graunt, citizen of London," London, 1662.

[2] T.R. Malthus, "Experience of the law on population," L. : Petrokom, 1793, 292 p.

[3] A. G. Volkov, "Pearl Raymond Demography," M. : Soviet Encyclopedia, 1975, p. 556. (The Great Soviet Encyclopedia, ch. ed. A.M. Prokhorov, vol. 19. pp. 1969-1978).

[4] P.K. Whelpton, "An empirical method of calculating future population," Journal of the American Statistical Association, 1936, no. 31, pp. 457-473.

[5] A.G. Vishnevsky, "Prospects for the development of Russia: the role of the demographic factor," M.: Russian National Library, 2003, 51 p.

[6] D. Meadows, "Limits of growth, 30 years later," translated from English, M.: Akademkniga, 2007, 342 p.

[7] H.A. Simon, "Rationality as a process and product of thinking," translated from English by K. B. Kozlova and M. A. Blanco, [Online]. Available: https://www2.econ.iastate.edu/tesfatsi/RationalityAsProcessAndProductOfThought.ElyLecture1978.Hsimon.pdf.

[8] J. Forrester, "World dynamics," translated from English, M.: AST; St. Petersburg: Terra Fantastica, 2003, 379 p.

[9] J. Forrester, "Dynamics of city development," translated from English, M.: Progress, 1974, 281 p.

[10] V.A. Tsybatov, "Macroeconomic modeling, forecasting and planning of regional development: a textbook," Samara: Publishing House of Samara State University, 2016, 316 p.

[11] Federal State Statistics Service: Official website, [Online]. Available: https://rosstat.gov.ru/folder/12781, [Accessed: 12 Jan 2024].

[12] The BFGS method or one of the most effective optimization methods, [Online]. Available: https://habr.com/ru/post/333356, [Accessed: 04 Dec 2023].

[13] S. Pattanayak, "Pro Deep Learning with TensorFlow: A Mathematical Approach to Advanced Artificial Intelligence in Python," Apress, 2019, 480 p.

[14] S. Lutfiani, M. Sri, and R. Hendrisman, "Forecasting the mortality rates of Indonesian population by using neural network," International Conference on Mathematics: Pure, Applied and Computation, IOP Conf. Series: Journal of Physics: Conf. Series, pp. 974-012030, 2018.

[15] N. Bheemanna and M.N. Megeri, "Prediction of India's demographic and economic variables using the neural network auto-regression model," International Journal of Statistics and Applied Mathematics, vol. 11, pp. 44-55.

[16] A.A. Khafalyan, "Industrial statistics. Quality control, process analysis, experiment planning in the STATISTICA package: textbook," M.: Rusains Publishing House, 2019, 384 p.

[17] T. Theophili, "Deep learning for search engines: textbook," 2020, 318 p. .

[18] O. Geron, "Hands-On Machine Learning with Scikit-Learn and TensorFlow: Concepts, Tools, and Techniques for Building Intelligent Systems: textbook," Jupiter 2020, 688 p. .

[19] S. Haikin, "Neural Networks: textbook," 2019, 1408 p.

[20] S. Russell and P. Norvig, "Artificial Intelligence: A Modern Approach: textbook," Pearson, 2019, 1104 p.

[21] D. Practical, "Artificial Intelligence with Python," Williams, 2019, 448 p.

[22] M. Bernard, "Artificial Intelligence in Practice," Wiley, 2019, 605 p.

[23] Statistica software package, [Online]. Available: https://statsoft.ru, [Accessed: 04 Dec 2023].

[24] M. F. H. Mohammad, "Comparison Markov Chain and Neural Network Models for forecasting Population growth data in Iraq," University of Kirkuk Journal For Administrative and Economic Science, 13(4), pp. 1-14, 2023.

[25] W. Rajesh, "Neural Network Based Mortality Prediction in Covid-19 Dataset," University of Kirkuk International Conference on Artificial Intelligence of Things, 2024.