Simulation of knowledge development in an innovation system based on neural network model

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Abstract. Innovative development is impossible without the support of scientific research capable of forming fundamentally new technological approaches. The process of knowledge development cannot be fully formalized, therefore, management decisions are made in conditions of uncertainty. The models developed on the basis of self-organization are the most effective for predicting the development of knowledge in the innovation system. On the basis of the developed recurrent neural network, the analysis of the influence of the state scientific and technical policy on the formation of the strategies of the actors of the national innovation systems of the BRICS countries is carried out. The determinants of the influence of the state scientific and technical policy on the development of knowledge in the innovation system are revealed.

1. Introduction

Scientific research is a key driver of economic growth and the development of national innovation systems (NIS). Fundamental research broadens the knowledge base and thus enables innovation processes, which in turn lead to the improvement or development of new products and services. Despite the fact that the benefits of fundamental research are manifold, they are often indirect and require a long period for their practical application [1, 2]. From the point of view of efficiency, the problem of justifying investments in fundamental research projects, which, by definition, are not capable of generating profit, remains a problematic issue. The rationale for investments of this kind is associated with factors that lie outside the economy [3, 4]. Economically, the most promising innovations are associated with applied research rather than fundamental research.

Technological development is impossible without the advancement of fundamental science capable of forming new technological approaches. Since it is impossible to fully formalize the process of producing scientific knowledge, management decisions in the field of possible scales and directions of funding for fundamental research are made under ambiguity. Research in this area was carried out using econometrics tools - classical statistical methods [5, 6]. The most important of these tools is multivariate linear regression with covariance matrix inversion. But modern innovative systems operate on big data, for which the use of linear regression or autoregression unreasonably simplifies the model [7, 8]. In the process of modeling the development of knowledge, it is necessary to take into account the cause-and-effect relationships of the diffusion of scientific results.
2. Forecasting the development of innovation systems

If we consider forecasting the development of innovative systems as a model for assessing efficiency, based on the interaction of actors making economic decisions based on certain indicators or patterns, then it is advisable to use econometric and balance models. Time series and autoregressive models take into account past dynamics, while stochastic models take into account random facts and events (political, social, etc.), which makes it difficult to formally describe causal relationships.

Most of the research on time series forecasting is devoted to regression models (linear, multiple, nonlinear), which are now almost never used, unlike autoregressive models. The most popular among them are autoregressive integrated moving average and its various modifications [9, 10]. For such models, the input data must be a stationary process. For non-stationary processes, which are the processes of development of national innovation systems, discrete differentiation is used in order to make the process stationary [11, 12]. Another subtype of autoregressive models is the autoregressive conditional heteroscedasticity model [13]. Models of this type are used when processing time series with high volatility. But due to the lack of accurate data, all known models give predictions with a large range of variations and are difficult to calculate.

A promising direction in predicting the development of innovative systems is an artificial neural network approach. In [14, 15], the use of an ensemble of neural networks is proposed. However, the results obtained were found to be unacceptable due to low productivity and training time.

3. Neural network model of knowledge development

It is proposed to model the development of knowledge in national systems for supporting scientific research on the basis of recurrent neural networks. The a priori structure of the model is unknown, and the factors influencing the operation of the model are of an evaluative nature and are fuzzy values and their influence is nonlinear. This requires choosing a model that will fit the data. Such models can be generated using empirical modeling methods [16, 17].

The models obtained on the basis of self-organization are the most effective for predicting the development of knowledge in the innovation system. It is proposed to use the group method of data handling [18, 19]. The feature of the method is that it allows you to build regression models and choose a model with a minimum number of parameters among them. An innovative research support system is represented by multiple entrances and one exit. The system can be modeled with a specific set of basic function components.

\[
Y = (x_1, \ldots, x_n) = \alpha_0 + \sum_{i=1}^{N} \alpha_i f_i, \tag{1}
\]

where \( x_1, \ldots, x_n \) - input indicators; \( Y \) - effectiveness of the national research support system; \( \alpha_i \) - coefficients; \( f_i \) - basic functions. The connection between the inputs and outputs of a self-organizing network can be represented by an infinite polynomial.

\[
y_n = \alpha_0 + \sum_{j=1}^{N} \alpha_j x_j + \sum_{i=1}^{N} \sum_{j=1}^{N} \alpha_{ij} x_i x_j + \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} \alpha_{ijk} x_i x_j x_k + \ldots, \tag{2}
\]

The neural network was built from a sequence of simple polynomials and is a polynomial neural network in which the sigmoidal node processing function is replaced with a polynomial function. Inputs are defined as delayed (shifted by a unit of time) elements of the predicted time series.

In contrast to the iterative method in neural networks with backpropagation through time, errors are minimized by progressive approximation using the least squares method. Training in this case is reduced to solving a system of equations. There is another advantage of this network - it cannot overtrain. To assess the forecast accuracy, the metric of the mean absolute error was used:

\[
M = \frac{1}{N} \sum_{i=1}^{N} \frac{Y_i - \hat{Y}}{Y_i}, \tag{3}
\]

\[
Y^2 = x^2 + Y^2.
\]
Using the model (2), the forecasting of the level and dynamics of indicators of the effectiveness of the development of scientific and technical activities of the national innovation systems of the BRICS countries was carried out (table 1). As an indicator of the effectiveness of knowledge development, a normalized index was used, including the functional, process and object components of the analysis (institutional environment; infrastructure; organizations; financing; human capital; knowledge generation; knowledge absorption; knowledge diffusion).

| Year | Russia | Brazil | China | India | South Africa |
|------|--------|--------|-------|-------|--------------|
| 2022 | 0.503  | 0.471  | 0.847 | 0.236 | 0.208        |
| 2023 | 0.489  | 0.512  | 0.851 | 0.306 | 0.192        |
| 2024 | 0.475  | 0.548  | 0.793 | 0.371 | 0.242        |
| 2025 | 0.482  | 0.523  | 0.802 | 0.386 | 0.217        |
| 2026 | 0.491  | 0.435  | 0.775 | 0.353 | 0.223        |

On the basis of the developed model, the analysis of the influence of the state scientific and technical policy on the formation of strategies of the actors of the national systems for supporting fundamental research in the BRICS countries is carried out. The activities of actors are significantly influenced by such characteristics as the size classes of scientific and educational organizations.

The results of the analysis of indicators of the scale of scientific and technical activities of the BRICS countries and the dynamics of their change indicate that Russia is inert in the innovation system. High indicators of knowledge development are mainly formed in high-dimensional classes due to their dominance. Therefore, when developing appropriate policy measures, one should proceed from such tasks as overcoming the scientific and technical passivity of large organizations and increasing the share of classes of active scientific organizations of small and medium size. Effective measures are needed to create framework conditions in the field of scientific and technological development for the implementation of directions for the development of structural factors.

The determinants of the influence of the state scientific and technical policy on the development of knowledge in the innovation system are revealed:

- development of the scientific and methodological base of the scientific and technical sphere;
- financing and attracting investments in the scientific and technical sphere;
- development of human resources in the field of science and technology;
- modernization of the material and technical base in the scientific and technical sphere;
- information support of the scientific and technical sphere;
- stimulating business entities to develop and implement innovations;
- development of infrastructure to support scientific and technical activities.

In the short, medium or long term, different intensities of fundamental research in different thematic areas may be required, which in turn may lead to the need to vary the amount of resources allocated to these thematic areas. The interdependence of some areas of basic scientific research in the short, medium or long term may require an analysis of interdisciplinarity and the identification of possible synergy effects in joint research in these areas. The presence of weaknesses in some areas of fundamental research in the analyzed period, as well as the presence of time lags between obtaining the results of fundamental research and the practical use of technologies based on these results, can affect the relevance of the results of scientific activities.

Actor's preferences for research funding sources were analyzed using complementarity and substitution effects. As a measure of the change in the preferences of the actors, we used their shift...
towards the preferential internal or external funding of scientific research. A significant advantage of the study was the focus on the primary factors affecting the change in actors’ preferences when choosing sources of research funding. The primary factors of the neural network model are associated with the characteristics of funding, institutional environment, state science and technology policy, and human capital. As a result of the study, it was found that China is the most consistent in building the necessary research potential. In this country, there is a positive complementarity effect with a shift in the preferences of actors towards domestic sources. This dynamics is largely due to the following factors: developed infrastructure; high level of organization; traditionally strong measures of state support for universities. A different picture is observed for Russia, where there is a shift in the interests of actors towards the use of external sources. This effect is largely due to the economic downturn, as well as the underdevelopment of the adaptive potential.

4. Conclusion
The developed neural network model was used to identify areas for improving the national support system for fundamental research in Russia. China’s innovation performance was chosen as a benchmark for analyzing the opportunities for innovation growth in Russia. Since, according to the results of the study, China is the leader among the developing countries of the BRICS.

A comparative analysis of the results of the scientific and technological development of Russia and China showed a strong lag in the development of the national innovation system of Russia. The complex of scientific and technical measures taken in China is quite fully correlated with the solution of the problems of the investment stage of development. In addition, the national innovation policy uses tools to facilitate the transition to the next stage of technological development. China, with the help of active measures of indirect incentives, ensured an inflow of foreign investment in science and carried out a transfer of foreign technologies.

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