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Modeling of Regional Innovation Spillover Effects Based on DEA Malmquist Index

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***Abstract*—The article presents the results of a study of innovative spillover effects using Data Envelopment Analysis (DEA) tools. The study is novel, in that an assessment methodology has been developed based on the Malmquist index and an output-oriented DEA model has been built to analyze the dynamics of the regional innovation system development. The development of innovative systems at the regional and national levels has been assessed, the Malmquist Index has been calculated, the characteristics of the regions have been determined taking into account the evaluation of spillover effects, and conclusions have been drawn on the dynamics of the development of innovative activities. The results of the study indicate the presence of positive innovative spillover effects over 2005–2017 in the Russian economy.**

***Index Terms*—Non parametric Model, Data Envelopment Analysis, Malmquist Productivity Index, Regional Innovations System, Spillovers.**

I. INTRODUCTION

The topicality of this work lies in the need to study innovative spillover effects of the diffusion of innovations and to obtain a formalized assessment of the impact of diffusion processes of innovations and their externalities on structural shifts and economic growth in regional innovation systems.

One of the methodological approaches to assessing the impact of innovative spillover effects of the diffusion of innovations on the Russian economy growth and the regional innovative development is the comparison of the invested resources and the results of innovative processes as well as evaluation of the quantitative and qualitative changes in the national economy structure over time. A relevant tool for evaluating and researching the comparative effectiveness of economic systems is the use of the Data Envelopment Analysis (DEA) method [1].

The purpose of this study is to develop new methods of economic and mathematical modeling for the diagnosis of regional structural changes, to evaluate the spillover effects of diffusion of innovations using the DEA Malmquist Index methodology.

To achieve this goal, the following problems have been solved:

- determination of the methods for evaluating innovative spillover effects and substantiation of indicators for mathematical model construction, generating a research sample based on the Russian regional data;
- development of a methodology for using the DEA Malmquist Index to evaluate innovative spillover effects;
- application of the developed tools for assessing the efficiency dynamics of the development of regional innovative systems of Russia from 2005 to 2012.

II. THEORETICAL ANALYSIS

Over the past 20 years of economic reforms in Russia, a course has been set for the development of innovations, large-scale structural transformations have been implemented in the higher education and science sector, and numerous scientific and technical programs have been initiated, funding for innovations was increased, in all sectors of the economy have undergone significant changes.

To substantiate the goals and nature of structural transformations, it is important to obtain a formalized assessment of the results of state innovation policy. Direct results are reflected in state statistical reporting. These are a number of indicators, such as patents, R&D expenses and other quantitative indicators [2], [3]. However, indirect results and effects in the form of structural changes are much more difficult to measure.

Spillover oriented approaches can be a tool for evaluating the public policy effectiveness. An innovative spillover as an overflow is the result of diffusion and transfer of technologies and innovations in the form of processes of intellectual property transfer, support of innovative enterprises, the mutual transfer of personnel between industry and the R&D sector [4], [5].

The present study uses the DEA and Malmquist Index tools to compare the economic indicators of the research and innovation activity of the Russian Federation constituent entities over the 2005–2012 period in order to determine the direction and assess the nature of innovative spillover effects.

This approach assumes a non-specific set of indicators reflecting these indirect effects which would be statistically significant and available for the study.

III. RESEARCH METHODOLOGY

A. Data

To evaluate innovative spillover effects, indicators were used to assess the qualitative structural changes that occurred in the economy under the influence of state innovation policy. Systemic macroeffects in this area consist of structural changes and increased indicators of innovative activity expressed primarily in the growing share of high-tech products in the GRP structure, rise in the number of innovations introduced and the results of intellectual property used, and the growth of investment effort in the economy and financial support for innovation activity investment processes [6]–[8].

The specific character of the innovation process lies in the long life cycle of the innovation project, in contrast to projects involving traditional products, and the coverage of different links: research and development, introduction of innovations into practice, launching products into the market, and obtaining an economic effect. Therefore, to assess the innovation policy effectiveness, a 5-year time lag was chosen, which means that the resources invested in the innovation system in 2005 were converted into the results of 2012, and the resources of 2010 led to the results in 2017.

The regional innovation systems effectiveness was assessed on the data from 80 regions, since a number of Russian regions do not have comparable indicators in the 2005–2017 [9].

The study used the following figures as indicators of innovation for evaluating innovative spillover effects. Input parameters for modeling are the resources invested to maintain the functioning of the system:

- R&D Personnel is research and development personnel, pers.;
- R&D Finance is all domestic current and capital costs for research and development, million rubles;
- issued patents are the issuance of patents and certificates for the intellectual activity outcomes, units;
- R&D companies are innovative enterprises, in the constituent documents of which one of the types of economic activity is indicated as “Research and Development”, units.

The indicators of activity, the growth of which contributes to the development of the region economy, leads to an increase in income or for other reasons is desirable from the point of view of the researcher, are used as outputs. The following parameters were selected as output parameters – results in the form of innovative spillover effects:

- hi-tech share in GRP, % is the share of high-tech and knowledge-based industries in the gross regional product of the region of the Russian Federation; it characterizes the technological structure of the economy;
- investment in fixed assets, % is the share of investments in fixed capital to GRP; it characterizes the investment activity of the Russian regions. The acceleration of investment growth in fixed capital in the economy is an important indicator of the Russian Federation Government;
- utility patents are the data on the use of intellectual property, units.

All statistical indicators for all analyzed objects are translated into comparable values.

B. DEA Malmquist Index Modeling

The methodology for assessing the dynamics of region innovative development and innovative spillovers is based on the application of the DEA model with the Malmquist Productivity Index. DEA is a linear programming methodology that uses input and output data for a group of homogeneous objects in order to build a piece-wise linear production frontier. The DEA provides estimation of the efficiency relative to the best practices under the condition that the technology is fixed at current level. To construct the frontier, linear programming problems are solved (for each object in the sample, a separate problem is formulated and solved). The degree of technical inefficiency of each object is defined as the distance between the observed data point and the frontier. DEA makes it possible to obtain quantitative evaluation of the analysable entities usually called decision-making units (DMU).

Currently there are different types of DEA models depending on orientation (input-oriented, output-oriented), returns to scale (constant return to scale (CRS), variable returns to scale (VRS)), distance function, frontier type and other aspects [10]. In input-oriented model, the DEA method constructs the frontier by searching for the maximum possible proportional reduction of input data with constant output levels for each object. In the output-oriented model, the DEA method dines the maximum proportional increase in production output under assumption fixed input levels. These two approaches give the same estimations of technical efficiency when applying CRS model, but are unequal in VRS model. In this research, we apply CRS model.

The Malmquist index is used to evaluate the technological efficiency obtained for relatively different sets of objects [11]. The Malmquist index measures the total factor productivity change of a DMU between two periods. It is defined as the product of a change in efficiency (catch-up) and technological change (shift of the border). A change in efficiency reflects the extent to which the DMU improves or deteriorates its effectiveness, while technological changes reflect a change in the frontiers of efficiency between two periods [12].

The total factor productivity (TFP) using the Malmquist index methods change between two data points (e.g., those of a particular region in two adjacent time periods) by calculating the ratio of the distances of each data point relative to a common technology. The Malmquist TFP change index in output-orientated DEA model between period t and period $(t+1)$ is:

$$M_o\left(y_{t+1}, x_{t+1}, y_t, x_t\right) = \\ = \left(\frac{d_o^t\left(x_{t+1}, y_{t+1}\right)}{d_o^t\left(x_t, y_t\right)} \cdot \frac{d_o^{t+1}\left(x_{t+1}, y_{t+1}\right)}{d_o^{t+1}\left(x_t, y_t\right)}\right)^{0.5}, \quad (1)$$

where (x_{t+1}, y_{t+1}) and (x_t, y_t) represent the input and output vector of the period $(t+1)$ and t, respectively, the notation $d_o^t\left(x_t, y_t\right)$ represents the distance from the period t to the period $(t+1)$ technology.

A value of M_o greater than 1 will indicate positive TFP growth from period t to period $(t+1)$. A value of M_o less than 1 indicates a TFP decline. M_o is the geometric mean of two TFP indices. The first is evaluated with respect to period t technology and the second with respect to period $(t+1)$

technology. Anquivalent decomposed form of the total factor productivity index [13], [14] is:

$$M_o\left(y_{t+1}, x_{t+1}, y_t, x_t\right) = \frac{d_o^{t+1}\left(x_{t+1}, y_{t+1}\right)}{d_o^t\left(x_t, y_t\right)} \times \\ \times \left(\frac{d_o^t\left(x_{t+1}, y_{t+1}\right)}{d_o^t\left(x_t, y_t\right)} \cdot \frac{d_o^{t+1}\left(x_{t+1}, y_{t+1}\right)}{d_o^{t+1}\left(x_t, y_t\right)}\right)^{0.5}. \quad (2)$$

Let's consider the first factor in (2) named as technical efficiency change ($EFFCH$):

$$EFFCH = \frac{d_o^{t+1}\left(x_{t+1}, y_{t+1}\right)}{d_o^t\left(x_t, y_t\right)}. \quad (3)$$

$EFFCH$ is the change in the output-oriented measure of technical efficiency between periods t and $(t+1)$, it shows how the ratio of actual outputs to potential has changed. EFFCH indicates the capability of a DMU to catch up with more efficient DMUs.

The second factor in (2) is technological change ($TECHCH$):

$$TECHCH = \left(\frac{d_o^t\left(x_{t+1}, y_{t+1}\right)}{d_o^t\left(x_t, y_t\right)} \cdot \frac{d_o^{t+1}\left(x_{t+1}, y_{t+1}\right)}{d_o^{t+1}\left(x_t, y_t\right)}\right)^{0.5}. \quad (4)$$

$TECHCH$ is the potential index, the geometric mean of two relations, which characterizes the shift of the potential technology frontier between period t and $(t+1)$. In other words, the last relation reflects a change in the technological efficiency of the evaluated object caused by a shift in the effective boundary.

The TFP index can be represented in the form of such factors as the change in efficiency and the technical change. Let for a time period t, $t = 1, \ldots, T$, DMU_i, $i = 1, \ldots, N$, use P inputs to produce S outputs. In a particular time period t let's define:

y_i is a $S \times 1$ vector of output quantities for the DMU_i;
x_i is a $P \times 1$ vector of input quantities for the DMU_i;
Y is a $N \times S$ matrix of output quantities for all N DMU_i;
X is a $N \times P$ matrix of input quantities for all N DMU_i;
λ is a $N \times 1$ vector of weights;
ϕ is a scalar.

To calculate $M_o\left(y_{t+1}, x_{t+1}, y_t, x_t\right)$, it is necessary to solve the following linear programming problems [15]:

$$\left(d_o^t\left(x_t, y_t\right)\right)^{-1} = \max_{\phi,\lambda} \phi, \quad (5)$$

such that

$$-\phi y_{i,t} + Y_t\lambda \geq 0, \quad -x_{i,t} + X_t\lambda \geq 0, \quad \lambda \geq 0;$$

$$\left(d_o^{t+1}\left(x_{t+1}, y_{t+1}\right)\right)^{-1} = \max_{\phi,\lambda} \phi, \quad (6)$$

such that

$$-\phi y_{i,t+1} + Y_{t+1}\lambda \geq 0, \quad -x_{i,t+1} + X_{t+1}\lambda \geq 0, \quad \lambda \geq 0;$$

$$\left(d_o^t\left(x_{t+1}, y_{t+1}\right)\right)^{-1} = \max_{\phi,\lambda} \phi, \quad (7)$$

such that

$$-\phi y_{i,t+1} + Y_t\lambda \geq 0, \quad -x_{i,t+1} + X_t\lambda \geq 0, \quad \lambda \geq 0;$$

$$\left(d_o^{t+1}\left(x_t, y_t\right)\right)^{-1} = \max_{\phi,\lambda} \phi, \quad (8)$$

such that

$$-\phi y_{i,t} + Y_{t+1}\lambda \geq 0, \quad -x_{i,t} + X_{t+1}\lambda \geq 0, \quad \lambda \geq 0.$$

Tasks (5)–(8) must be calculated for each DMU in the sample. Hence the total number of linear programming problems for N DMUs and T time periods is $N \cdot (3T - 2)$.

IV. Results

Analysis of Malmquist productivity index and decomposition results from data of 80 regions of the Russian Federation allow present the tendency of regional innovation system development (Table I, Table II). The Table I contains regions with Malmquist index greater than 1 ($M_o > 1$).

The Table II contains regions with Malmquist index greater than 1 ($M_o < 1$).

The results (Table I) demonstrate a progress respectively productivity improvement in 47 regions (58.75%) during this period. 33 regions (41.25%) show productivity decline (regress) during investigated time period (Table II).

Analysis the evolution of the same DMUs over time involves calculating national average ratings (Fig. 1). The decomposition into the two components additionally demonstrates that the part of the improvement was attained through the technical change, rather than through the efficiency change of the relatively inefficient regions catching up with efficient ones. The national average for the total factor productivity of 80 regions is 1.128, which is greater than 1; total factor productivity is growing and the growth rate is 12.8%. It denotes that the technical efficiency reduces the difference with the optimal region on the frontier.

If $EFFCH$ >1, it denotes that the technical efficiency reduces the difference with the optimal DMU. If $EFFCH <$ 1, the technical efficiency increases the difference with the optimal DMU. The national average technical efficiency change index is 0.276, less than 1. It objectively indicates that the gap between the level of innovative systems development has significantly increased by the regions during the selected time period.

The technological change index TECHCH denotes the degree of technical advancement or technical innovation. If TECHCH $>$ 1, it means the technical advancement, and TECHCH $<$ 1 represents the technology possesses recessionary tendency. As seen from index decomposing, the national average of the technological change index is 4.081, greater than 1.

In order to measure how productivity divergences between region innovation systems change in 2012–2017 we identified three types of regions depending on the growth rate (Table III). Some of the regions (32.50%) demonstrate relatively low rates of region innovation system development, and 26.25% of the

Table I
MALMQUIST INDEX MEANS FOR THE REGIONS WITH ASCENDING PRODUCTIVITY

Region	EFFCH	TECHCH	M_o
Ivanovo region	8.387	3.078	25.815
Kursk region	3.817	4.622	17.641
Lipetsk region	2.950	4.016	11.845
Kemerovo region	4.421	1.981	8.758
Smolensk region	3.630	2.322	8.430
Tomsk region	3.153	2.418	7.623
Moscow	1.000	7.438	7.438
Nizhny Novgorod region	1.000	7.105	7.105
Kurgan region	2.886	1.668	4.814
Penza region	1.165	3.907	4.553
Republic of North Ossetia-Alania	1.298	3.477	4.515
Primorsky region	0.704	5.817	4.097
Yaroslavskaya region	1.171	3.434	4.020
Komi Republic	1.080	3.385	3.655
Tyumen region	0.365	9.247	3.375
Irkutsk region	0.553	4.517	2.497
Republic of Ingushetia	2.804	0.882	2.473
Krasnoyarsk region	0.248	9.208	2.283
Orenburg region	0.289	7.548	2.179
Pskov region	0.505	4.230	2.134
Leningrad region	1.000	2.099	2.099
Republic of Khakassia	1.081	1.799	1.945
Saint Petersburg	0.968	1.937	1.875
Magadan region	0.403	4.550	1.834
Altai Republic	1.208	1.444	1.744
Tver region	0.221	7.775	1.722
Volgograd region	0.157	10.881	1.707
Republic of Bashkortostan	0.307	5.439	1.672
Novgorod region	0.185	8.695	1.609
Vologodskaya region	0.203	7.505	1.521
Udmurt republic	0.247	5.844	1.443
Transbaikal region	0.192	7.282	1.399
Republic of Tatarstan	0.307	4.281	1.315
Chechen Republic	1.758	0.743	1.306
Kaluga region	0.220	5.857	1.289
Perm region	0.108	11.532	1.243
Republic of Kalmykia	0.908	1.319	1.197
Arkhangelsk region	0.164	7.184	1.175
Khabarovsk region	0.232	4.976	1.154
Kamchatka region	0.208	5.340	1.113
Stavropol region	0.148	7.473	1.109
Oryol region	0.104	10.458	1.085
Novosibirsk region	0.210	5.081	1.069
Kabardino-Balkarian Republic	0.163	6.432	1.046
Murmansk region	0.110	9.269	1.019
Chelyabinsk region	0.134	7.492	1.006
Kaliningrad region	0.187	5.362	1.002

regions are characterized by a rather high growth of region innovation system TFP.

V. CONCLUSION

The article presents a study of the functioning and efficiencies assessment of innovation systems. DEA model for the measurement of regional innovation systems' efficiency and Malmquist index was calculated.

Based on the calculation of the Malmquist index, we were able to conclude that positive spillovers and, accordingly, the positive effects of innovation policy over the 2005–2017 were shown by the regions with Malmquist index greater than 1. Over the study period, these regions showed a rise in the effectiveness of regional innovation systems, taking into

Table II
MALMQUIST INDEX MEANS FOR THE REGIONS WITH DESCENDING PRODUCTIVITY

Region	EFFCH	TECHCH	M_o
Republic of Sakha (Yakutia)	0.146	6.742	0.982
Chukotka Autonomous region	1.000	0.948	0.948
Republic of Buryatia	0.162	5.811	0.943
Vladimir region	0.120	7.671	0.917
Voronezh region	0.121	7.526	0.909
Republic of Karelia	0.167	5.305	0.884
Tambov region	0.132	5.839	0.770
Sakhalin region	0.292	2.595	0.758
Omsk region	0.087	8.446	0.737
Ryazan region	0.120	5.675	0.681
Amurskaya region	0.096	6.872	0.657
Moscow region	1.000	0.659	0.659
Samara region	0.102	6.432	0.656
Altai region	0.126	5.025	0.635
Astrakhan region	0.099	5.982	0.591
Republic of Dagestan	0.076	7.381	0.564
Saratov region	0.081	4.977	0.403
Ulyanovsk region	0.055	6.367	0.349
Bryansk region	0.079	4.106	0.325
Belgorod region	0.050	6.475	0.322
Kirov region	0.088	3.380	0.298
Republic of Mordovia	0.070	3.952	0.275
Chuvash Republic	0.085	3.262	0.276
Jewish Autonomous region	0.319	0.780	0.249
Sverdlovsk region	0.132	1.883	0.248
Mari El Republic	0.013	17.527	0.225
Rostov region	0.135	1.628	0.219
Tyva Republic	0.134	1.393	0.186
Krasnodar region	0.040	4.022	0.160
Tula region	0.044	3.747	0.164
Karachay-Cherkess Republic	0.078	1.783	0.138
Kostroma region	0.021	2.372	0.050
Republic of Adygea	0.077	0.564	0.044

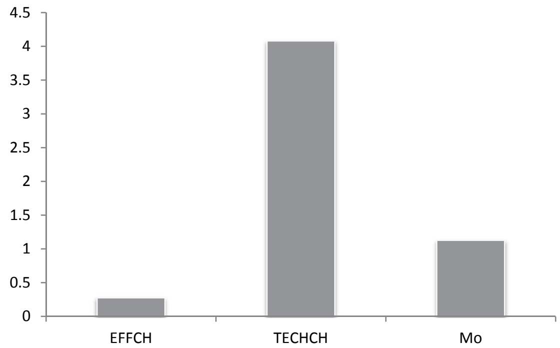

Figure 1. Averages of technical change and efficiency change.

Table III
DYNAMICS ASSESSMENT OF THE REGION INNOVATION SYSTEM DEVELOPMENT BASED ON THE MALMQUIST INDEX M_o

Region Type	Number of regions	
	Regions, units	Regions, %
Rapid growth ($M_o > 2$)	21	26.25
Growth ($2 \geq M_o \geq 1$)	26	32.50
Lack of growth ($M_o < 1$)	33	41.25

account the use of available resource, which made it possible to record the improvement of indirect results of innovative effort in the region.

A significant factor determining the increase in the regional innovation system effectiveness in the Russian Federation is structural technological changes and the increased share of high-tech economy.

At the same time, the constructed model objectively confirms the conclusion that there is a large gap between the leading regions and the regions in which the input innovative resources do not lead to significant innovative structural shifts in economic development at the macroeconomic level.

The research results consist of the creation of approaches for the innovative spillover effects assessment and the development of the methodology and tools for regional innovative development research.

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