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Modeling of Regional High Education Systems' Efficiency by Data Envelopment Analysis

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***Abstract*—The article presents a study of the functioning of higher education systems at the regional level in terms of their productive efficiencies. The purpose of this research is to determine the regional higher education systems' effectiveness using a Slack-Based Measure of efficiency (SBM), which is a variant of the Data Envelopment Analysis (DEA). The novelty of the study is the performance of modified DEA model with a set of special variables for analysis of regional higher education systems. This multidimensional model allows construct efficiency frontier consisting of region set, which are best-practice of higher education systems. The slacks which are needed to push the decision making unit to the frontier (target) were calculated for the inefficient regions. The resulting regions ranking and identifying the best-practice examples in terms of the functioning effectiveness of higher education systems provide an opportunity for objective decision-making on the development of education systems.**

***Index Terms*—decision making, data envelopment analysis, slack-based measure, education, regional higher education system**

I. Introduction

The effectiveness of the national higher education system contributes significantly to the economic growth and international competitiveness of the country. These trends actualize research aimed at assessing the effectiveness of higher education systems.

In the context of increasing transparency towards the state and society and increasing interest in the effectiveness of education systems in all countries, the development of modern assessment tools is now in demand. One of the tools relevant to the sphere of education for evaluating the effectiveness of a set of homogeneous economic systems is the Data Envelopment Analysis (DEA) method.

This study presents the results of evaluating the effectiveness of higher education systems in the Russians regions in terms of correlation of input parameters and the results of their operation.

The purpose of this research is to determine the regional higher education systems' efficiency using a Slack-Based Measure of efficiency (SBM), which is a variant of the DEA. This multi-dimensional model allows construct efficiency frontier consisting of region set, which are best practice of higher education systems.

To achieve this goal, the following stages were implemented:

- a set of indicators to assess the effectiveness, quantitatively reflecting the input and output resources to ensure the functioning of regional educational systems is defined and justified;
- the modified SBM model under the non-increasing returns-to-scale assumption is proposed;
- the estimation of efficiency of Russian regional educational systems on the basis of DEA modelling is made;
- the conclusions of the study were determined.

II. Theoretical Analysis

Significant investments in higher education in all countries cause discussion of critical issues of determining the effectiveness and quality of higher education, as well as finding ways to improve the performance of universities.

However, in the trends of integration and inter-determinism of economic growth, economics and education, it is necessary to shift the focus of research from the popular rankings of individual universities as universal measures of performance to the study of the effectiveness of the regional system of higher education in general, taking into account the context of the region [1]–[3].

The effectiveness of the regional system of higher education and the synergetic effect of interaction between the subjects of the regional economy, resulting from the targeted provision of human resources and intellectual products to the needs of regional development, affect the economic development of the region, and the strengthening of cooperative ties between its individual elements creates the preconditions for sustainable economic growth.

Education, science and industry, regional or corporate development: each area today demand modern assessment tools that meet user needs and reflect the current state of each of them in terms of increased transparency to the state and society and increased interest in the effectiveness of education systems.

The application of modern mathematical models and methods makes more objective the quantitative evaluation of complex multi-factor system more objective. The use of DEA seems to be a perspective method for a comprehensive study of the higher education systems' performance, as demonstrated in classic essential works in this field [4]–[6].

The measurement of the effectiveness boundary is carried out using the direct construction of the production function by the methods of mathematical statistics. Determination of the maximum efficiency is possible on the basis of the construction of the so-called data envelope by linear programming. DEA concentrates on the identification of examples of so-called best

TABLE I
INDICATORS FOR ASSESMENT THE EFFECTIVNESS OF HIGH EDUCATION INSTITUTES IN REGIONS

	Title	Indicators	Interpretation
Inputs	COSTS	Expenses for 1 student, thousand rubles	Funding of universities from all sources per student per student
	ASSETS	The cost of fixed assets per student, thousand rubles	Characteristics of material and technical provision of the educational process per student
Outputs	PUBL	The total number of publications per 100 employees of academic staff, units	Characteristics of the academic productivity of research and development
	EMPL	The share of employed students in the total output of students, %	Characteristics of the demand for graduates of the regional labour market
	R&D	Share of R&D income in total income, %	The ratio of the amount of funds received from R&B to the total amount of funds received by the educational organization

practices, rather than any average trends in contrast to the regression analysis.

DEA does not require time-series data for the inputs and outputs of individual objects unlike econometric modeling. It is possible to calculate the relative effectiveness of each object using DEA.

The method eliminates the problem of heteroscedasticity that exists in parametric modeling.

III. RESEARCH METHODOLOGY

A. Data and Indicators

A system of relevant indicators characterizing the input resources and output results of regional educational systems was formed for the DEA.

To calculate the technical efficiency of the regional higher education systems, a sample of data on 769 universities at the time of this study in early 2018 from 80 regions of the Russian Federation was formed.

In the preparation of indicators for DEA modeling were selected indicators of official statistical reporting of universities and data of Federal State Statistics Service and Ministry of Education and Science [7], [8].

As input parameters were selected characteristics of material and technical support of the educational process in the form of property value and fixed assets of universities per student, as well as financial support of the educational process in the form of funding of universities from all sources per student.

The results of regional higher education systems' activities are expressed in the demand for "manufactured products" of universities. Therefore, the output parameters are expressed in the number of trained and employed students in the region, in the volume of revenues from R&D and the number of scientific publications.

The system of input and output parameters and their interpretation for the analysis of the effectiveness of regional higher education systems using DEA is given in Table I.

The peculiarity of the choice of these indicators for this study is that for the output indicators was used not normalized indicators: the total number of publications and employed graduates, which allows to take into account and more adequately reflect in the resulting estimates the size and scale of the functioning of higher education systems at the regional level, in accordance with the high differentiation of territorial scales and levels of regional differences in the regions of the Russian Federation.

All output indicators indirectly reflect the level of regional development, taking into account the interdependence of the functioning of universities and the region, and indirectly assess the nature of this interaction between universities and the region.

B. DEA Modeling

The DEA is a multidimensional method for measuring the relative efficiency of a set of decision units (DMUs) described by a variety of variables acting as inputs and outputs. DEA is a non-parametric model, it allows for multiple inputs and outputs to be considered simultaneously.

The DEA is based on solving linear programming task for maximizing of DMU products (outputs) with a given amount of resources (inputs) or minimizing the resources (inputs) with a given level of output products (outputs). To solve the linear programming task, a DEA-model is built. It considers the relation of weighted output variables corresponding to the results of the DMU activity to the weighted input variables corresponding to the used DMU resources. In the DEA-method it is necessary to compare outputs-inputs of the DMUs in order to obtain relative efficiency estimates. DMUs that have maximum efficiency values are selected, and envelope of efficiency can be built. It allows to set the best practice DMU for a given combination of inputs. Those DMUs that receive the highest scores are at the frontier and become benchmarks for other DMUs in the sample [9].

The technical efficiency of a certain object is understood as the ratio of the goods and services produced to the resources used. DEA provides a comparison of DMUs which are given in various units or in different scales.

The DMU is effective if there are no more opportunities to reduce resources or increase production. Then failure is an excess or deficiency of an ineffective DMU. For ineffective

DMUs, changes in baseline values are determined to improve efficiency.

Currently there are several different types of DEA model that allow to take into account specific factors, such as the priority of parameters, returns to scale, risks, etc. [10].

Models can be input-oriented when input data (resources) are minimized in order to get fixed results or output-oriented when outputs are maximized using a given amount of resources.

The model can be adjusted for scale variation of data.

Let consider the Slacks-Based Measure (SBM) DEA model. SBM refers to additive models that maximizes the sum of input and output slacks for each DMU. The model provides a cumulative measure of all the inefficiencies that the DMU can demonstrate at its inputs and outputs in accordance with the Pareto-Koopmans efficiency concept. This model uses a special measure (Slacks-Based Measure), which makes the evaluation of the effectiveness of the invariant to the units of measure used for various inputs and outputs [11].

The method determines a target for DMU which is a strong effective point on the border furthest from the estimated DMU. The application of this approach is due to the task of evaluating regional higher education systems by the fact that regions should focus on more distant targets.

Let consider n DMU associated with m inputs and s outputs.

The input and output vectors of DMU$_j$, $j = 1, \ldots, n$, be $X_j = (x_{1j}, x_{2j}, \ldots, x_{mj})$ and $Y_j = (y_{1j}, y_{2j}, \ldots, y_{sj})$ respectively. DMU$_0$ is the target DMU, $X_0 = (x_{10}, x_{20}, \ldots, x_{m0})$ and $Y_0 = (y_{10}, y_{20}, \ldots, y_{r0})$ are the input and output vectors of the target DMU$_0$ respectively. $z_i^- = (z_1^- 1, x_2^-, \ldots, z_m^-)$ and $z_r^+ = (z_1^+, z_2^+, \ldots, z_s^+)$ are input and output slacks respectively. $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)$ is a intensity vector.

$$\rho_I^* = \min_{\lambda, s^-, s^+} 1 - \frac{1}{m} \sum_{i=1}^{m} \frac{z_i^-}{x_{i0}} \tag{1}$$

s.t.

$$x_{i0} = \sum_{j=1}^{n} x_{ij}\lambda_j + z_i^- \ \ (i = 1, \ldots \ , m)$$

$$y_{r0} = \sum_{j=1}^{n} y_{rj}\lambda_{j\,\_} z_r^+ \ \ (r = 1, \ldots \ , s)$$

$$\lambda_j \geq 0 \ \ (j = 1, \ldots, n)\,, \ z_i^- \geq 0 \ \ (i = 1, \ldots, m)\,,$$

$$z_r^+ \geq 0 \ \ (r = 1, \ldots, s)\,.$$

Output-oriented SBM-model is as follows:

$$\frac{1}{\rho_O^*} = \max_{\lambda, s^-, s^+} 1 + \frac{1}{s} \sum_{r=1}^{s} \frac{z_r^+}{y_{r0}} \tag{2}$$

s.t.

$$x_{i0} = \sum_{j=1}^{n} x_{ij}\lambda_j + z_i^- \ \ (i = 1, \ldots \ , m)$$

$$y_{r0} = \sum_{j=1}^{n} y_{rj}\lambda_j - z_r^+ \ \ (r = 1, \ldots \ , s)$$

$$\lambda_j \geq 0 \ \ (j = 1, \ldots,)\,, \ z_i^- \geq 0 \ \ (i = 1, \ldots,)\,,$$

$$z_r^+ \geq 0 \ \ (r = 1, \ldots,)$$

Non-oriented SBM-model is as follows:

$$\rho_{IO}^* = \min_{\lambda, s^-, s^+} \frac{1 - \frac{1}{m} \sum_{i=1}^{m} \frac{z_i^-}{x_{i0}}}{1 + \frac{1}{s} \sum_{r=1}^{s} \frac{z_r^+}{y_{r0}}} \tag{3}$$

s.t.

$$x_{i0} = \sum_{j=1}^{n} x_{ij}\lambda_j + z_i^- \ \ (i = 1, \ldots \ , m)$$

$$y_{r0} = \sum_{j=1}^{n} y_{rj}\lambda_j - z_r^+ \ \ (r = 1, \ldots \ , s)$$

$$\lambda_j \geq 0 \ \ (j = 1, \ldots,)\,, \ z_i^- \geq 0 \ \ (i = 1, \ldots,)\,,$$

$$z_r^+ \geq 0 \ \ (r = 1, \ldots,)$$

$\rho*$ in the model belongs to the interval [0,1].

DMU is SBM efficient if its corresponding $\rho* = 1$. It means $z_i^- = 0$ $(i = 1, \ldots, m)$, $z_r^+ = 0$ $(r = 1, \ldots, s)$. Otherwise, if $\rho* < 1$, DMU are considered ineffective.

Models (1), (2) and (3) are fractional program, and they can be transformed into linear form.

In DEA modeling there are different choice of scaling types. Concept of returns-to-scale (RTS) is related to the shapes of best-practice frontiers which constructed by these models. Models (1), (2) and (3) are considered subject to the constant returns-to-scale (CRS) assumption.

If models include a condition of $\sum_{j=1}^{n} \lambda_j = 1$, we obtain non-increasing variable returns-to-scale (VRS) DEA models. If we add in models $\sum_{j=1}^{n} \lambda_j \leq 1$, we obtain non-increasing RTS (NIRS) DEA models. If we add in models $\sum_{j=1}^{n} \lambda_j \geq 1$, we obtain non-decreasing RTS (NDRS) DEA models.

The model can be adjusted for orientation and scale variation of data that is an essential part of DEA modeling for a particular subject area [12], [13].

Input-oriented models are based on a variation in resource, we proposed to use this approach in DEA model, as the management of regional higher education systems can be carried out through these factors in decision-making process. Simulation involves the choice of scaling. Using the CRS method implies that all regions can achieve the same level of operational efficiency. The scale effect in this model is absent, and this means that all regions should be able to get the same efficiency of education systems as larger regions that have better conditions for development and work under conditions of scale effect. However, if the variable return-to-scale is used, the risk of recognizing an ineffective DMU as effective increases. In particular, DMUs with very low or high values can be considered effective solely because of extreme values. In this study, for the leveling effect of the extreme values is proposed to use the non-increasing RTS model.

TABLE II
SBM SCORES OF REGIONAL HIGH EDUCATION SYSTEMS IN RUSSIA

DMU	SBM scores	DMU	SBM scores	DMU	SBM scores
Moscow	1	Kostroma region	0.59	Republic of Kalmykia	0.32
St. Petersburg	1	Novosibirsk region	0.57	Ulyanovsk region	0.31
Krasnodar region	1	Penza region	0.57	Republic of Buryatia	0.31
Nizhny Novgorod region	1	Chuvash Republic	0.55	Astrakhan region	0.30
Moscow region	1	Orenburg region	0.53	Republic of Adygea	0.29
Kursk region	1	Ivanovo region	0.53	Komi Republic	0.29
Tomsk region	1	Tyumen region	0.52	Republic of Ingushetia	0.28
Stavropol region	1	Mari El Republic	0.50	Smolensk region	0.28
Republic of Dagestan	1	Lipetsk region	0.49	Kabardino-Balkaria	0.28
Sverdlovsk region	0.89	Republic of Karelia	0.49	Kaliningrad region	0.26
Belgorod region	0.85	Novgorod region	0.48	Republic of North Ossetia–Alanya	0.25
Samara Region	0.85	Ryazan Oblast	0.46	Leningrad region	0.21
Rostov region	0.82	Vladimir region	0.45	Transbaikal region	0.20
Voronezh region	0.78	Chechen Republic	0.45	Altai Republic	0.20
Republic of Tatarstan	0.75	Irkutsk region	0.45	Arkhangelsk region	0.20
Tambov Region	0.75	Udmurtia	0.44	Kaluga region	0.18
Omsk region	0.73	Oryol Region	0.44	Amur region	0.16
Volgograd region	0.73	Tver region	0.44	Republic of Sakha (Yakutia)	0.16
Bashkortostan	0.72	Republic of Mordovia	0.40	Jewish Autonomous Oblast	0.15
Perm region	0.71	Kirov region	0.40	Murmansk region	0.14
Bryansk region	0.70	Saratov region	0.37	Kamchatka territory	0.14
Kemerovo region	0.67	Pskov region	0.37	Republic of Tuva	0.13
Tula region	0.66	Khabarovsk region	0.35	Chukotka Autonomous Okrug	0.13
Chelyabinsk region	0.65	Karachay-Cherkessiaia	0.34	Republic of Khakassia	0.12
Altai region	0.65	Krasnoyarsk region	0.34	Sakhalin region	0.11
Kurgan region	0.61	Vologodskaya Oblast	0.32	Primorsky Krai	0.09
Yaroslavskaya oblast	0.61	Magadan Region	0.32		

C. Results

As a result of the use of DEA-modeling on the data of 80 regional systems of higher education, the following estimates of technical efficiency and regional systems of higher education were obtained, presented in Table II.

The regions with the indicator value $\rho = 1$ proved to be the most technically efficient: Moscow, St. Petersburg, Krasnodar region, Nizhny Novgorod region, Moscow region, Kursk region, Tomsk region, Stavropol region, Republic of Dagestan. These regions demonstrate effective structure of inputs and outputs and balanced proportions of operating costs and results. Their experience should be analyzed in detail, studied and disseminated in benchmarking procedures in other regional high education systems in Russia.

After proportional reductions in inputs or increases in outputs, if a DMU cannot reach the efficiency frontier (to its efficient target), slacks are needed to push the DMU to the frontier (target).

The table III presents the results of SBM modeling for determining slacks that can provide quantitative assumption regarding the possibility of increasing the regions efficiency. If the DMU is not on the efficiency frontier, slacks determining of corresponding decrease in inputs or an increase in outputs are required, in order for the DMU can belong to the frontier.

Table IV shows the number of the regions falling within the indicated ranges of efficiency values.

Figure 1 shows a scatter chart that shows no strong correlation between the level of development of the region and the effectiveness of regional higher education systems. The regions with high integrated indicators of regional development were the best in terms of technical efficiency. However, there are underdeveloped regions with high rates of development of education systems. As possible drivers of the growth of regional higher education systems in such regions need to be strengthened funding.

D. Conclusion

The article presents a study of the functioning of higher education systems at the regional level in terms of their productive efficiencies. SBM DEA model for the measurement of higher education systems' efficiency at the regional level and slacks were used.

SBM model was constructed, the efficiency frontier for region set was made, for inefficient regions slacks was calculated.

The results confirm the absence of homogeneity among the Russian regions and high differentiation of regional systems of higher education, as well as high degree of educational inequality.

The presence of sufficiently effective regional systems of higher education in economically underdeveloped regions is established. There is a weak correlation between the level of

TABLE III
SLACK VARIABLE RESULTS OF INEFFICIENT REGIONAL HIGH EDUCATION SYSTEMS

DMU	Slack Movement				
	COSTS	ASSETS	R&D	PUBL	EMPL
Sverdlovsk region	−11.24	−28.28	0	0	0
Belgorod region	0	−80.43	0	2523.34	9.35
Samara Region	−18.27	−32.95	0	0	0
Rostov region	−6.73	−66.94	0	0	0
Voronezh region	−13.96	−44.95	0	0	0
Republic of Tatarstan	−7.56	−175.65	0	0	0
Tambov Region	−11.10	−59.95	0	857.52	4.17
Omsk region	−33.77	−19.90	0	0	0
Volgograd region	−36.50	−39.58	0	0	0
Bashkortostan	−33.48	−51.36	0	0	0
Perm region	−7.52	−213.91	0	530.93	5.59
Bryansk region	−15.49	−48.27	0	0	0
Kemerovo region	−26.60	−63.39	0	0	0
Tula region	−35.75	−39.25	0	0	0
Chelyabinsk region	−33.86	−94.98	0	0	0
Altai region	−43.85	−33.92	0	2108.14	0
Kurgan region	−19.41	−64.04	0	630.23	2.28
Yaroslavskaya oblast	−37.80	−77.89	0	0	1.40
Kostroma region	−34.86	−63.31	0	1822.96	4.19
Novosibirsk region	−47.38	−124.10	0	0	0
Penza region	−51.04	−25.15	0	0	0
Chuvash Republic	−30.82	−54.69	0	0	0
Orenburg region	−39.12	−75.32	0	0	0
Ivanovo region	−49.04	−89.08	0	702.51	1.93
Tyumen region	−65.85	−115.13	0	1406.19	0
Mari El Republic	−44.26	−95.68	0	278.20	4.04
Lipetsk region	−36.62	−71.10	0	0	0
Republic of Karelia	−72.64	−138.91	0	1915.10	8.30
Novgorod region	−61.07	−131.04	0	1473.31	7.23
Ryazan Oblast	−43.28	−73.32	0	0	0
Vladimir region	−46.85	−67.48	0	0	0
Chechen Republic	−27.21	−139.68	0	634.86	0.80
Irkutsk region	−70.76	−151.02	0	0	0
Udmurtia	−48.02	−85.42	0	0	0
Oryol Region	−40.51	−131.95	0	0	0
Tver region	−62.17	−100.46	0	0	0.81
Republic of Mordovia	−55.78	−215.84	0	608.74	2.49
Kirov region	−56.58	−67.49	0	0	0
Saratov region	−88.02	−179.73	0	0	0
Pskov region	−56.50	−124.09	0	707.52	2.74
Khabarovsk region	−85.15	−121.13	0	0	0
Karachay−Cherkess	−43.28	−127.70	0	256.23	2.62
Krasnoyarsk region	−137.70	−246.52	0	0	0
Vologodskaya Oblast	−69.28	−85.71	0	0	0
Magadan region	−104.25	−73.11	0	1049.70	3.84
Republic of Kalmykia	−51.95	−133.46	0	160.67	3.22
Ulyanovsk region	−77.59	−311.07	0	0	0
Republic of Buryatia	−67.90	−112.08	0	426.62	0
Astrakhan region	−78.69	−88.91	0	0	0
Republic of Adygea	−64.33	−186.38	0	689.25	2.50
Komi Republic	−110.14	−166.10	0	1012.72	1.92
Republic of Ingushetia	−75.17	−184.80	0	921.20	4.12
Smolensk region	−64.81	−298.74	0	0	0
Kabardino−Balkaria	−91.61	−200.74	0	1498.12	3.58
Kaliningrad region	−101.78	−254.42	0	0	1.20
Republic of North Ossetia–Alanya	−74.30	−129.43	0	0	0

CONTINUATION OF TABLE III

DMU	Slack Movement				
	COSTS	ASSETS	R&D	PUBL	EMPL
Leningrad region	−93.48	−87.25	0	347.48	1.15
Transbaikal region	−98.72	−143.04	0	0	0
Altai Republic	−131.01	−149.67	0	843.40	3.50
Arkhangelsk region	−158.47	−420.06	0	0	1.51
Kaluga region	−90.10	−261.82	0	0	0
Amur region	−135.29	−200.19	0	0	0
Republic of Sakha (Yakutia)	−211.23	−432.11	0	0	0.50
Jewish Autonomous	−119.33	−122.36	0	234.33	1.70
Murmansk region	−154.73	−136.57	0.70	771.40	0
Kamchatka Krai	−121.33	−198.18	0	0	1.24
Tyva Republic	−131.85	−172.04	0	376.77	1.75
Chukotka Autonomous Okrug	−228.48	−75.69	0	526.48	1.99
Republic of Khakassia	−123.35	−152.08	0	0	0.72
Sakhalin region	−148.13	−255.34	0	400.81	1.50
Primorsky Krai	−313.03	−1601.41	0	0	0

TABLE IV
AGGREGATED DEA RESULTS OF REGIONAL HIGH EDUCATION SYSTEMS EFFICIENCY

Indicators	The level of regional high education systems efficiency		
	High	Medium	Low
Value range of regional high education systems effectiveness	1	[0.3;1)	[0; 0.3)
Number of regions, units	9	23	48
Number of regions,%	11.25%	28.75%	60.00%

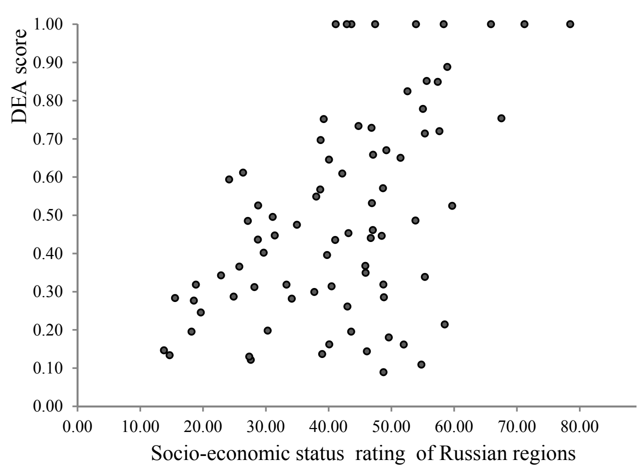

Fig. 1. Assesment of correlations DEA high education institutes in regions score and level of socio-economic status of regions

economic development of the region and the effectiveness of the regional system of higher education.

The proposed approach can be used as an analytical tool for the analysis, evaluation, ranking and differentiation of the structure of regions and regional higher education systems from the standpoint of efficiency and balance of their development.

The research results can be used to solve the problems of improving institutional management in the planning of reforms and transformations of regional higher education systems.

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