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Scientometric Methods for Identifying Scientific Leaders: New Mathematical Models

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Abstract—A new approach to the multidimensional assessment of research organizations is introduced. Based on the use of quantitative data, various types of research and development results are considered in the approach.

Keywords: scientific and technological activity, research and development, data sources, research organizations, organizational performance, peer groups, organizational assessment

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INTRODUCTION

The development of science, which is globally recognized as one of the major sources of new knowledge and technologies that drive economic growth, requires large-scale public and private investment. As estimated by UNESCO, gross expenditures on global research and development (R&D) in 2014 surpassed USD 1.5 trillion (UNESCO, 2016). According to national statistical data, Russia's domestic expenditures on R&D reached 943.8 billion roubles ($37.3 billion in terms of purchasing power parity) in 2016. Russia ranked tenth in terms of domestic R&D expenditures in the global ranking compiled by the National Research University Higher School of Economics (NRU HSE, 2017). Russia ranked sixth worldwide in terms of public funding allocated for civil R&D and fourth in terms of the number of research personnel.

The growing investment in science and new technology that can be observed in many countries is associated with expectations of a higher payoff, which has led to the integration of systematic monitoring and public performance assessment of R&D organizations. The assessment systems cover a range of research and analytical activities, mechanisms, and procedures focused on the analysis of scientific performance, identification of problems and barriers experienced by research organizations, as well as the elaboration of recommendations on how to tackle the related problems. The scale and form of specific measurement and assessment instruments and approaches applied depend on specific political aims and goals.

As an example, the research performance and quality assessment in the UK university sector is based on three groups of parameters: research results, the economic and societal impacts of these results, and the quality of the research environment[1]. The evaluation of research in Germany mostly targets scientific societies, which perform the auditing of their constituent institutes and conduct external assessment with the participation of national and foreign experts. The evaluation covers both organizational, administrative, and financial activities of organizations, as well as their scientific and technological performance (e.g., [1]).

The evaluation of research organizations of the Centre national de la recherche scientifique (CNRS) in France is implemented at two levels [2]. The French evaluation system involves the analysis of financial reporting, which is mandatory for all public organizations in France, as well as the research assessment, which is implemented at the following levels: thematic areas of research, programs and projects, institutes and laboratories, and individual researchers (CNRS, 2015).

Japan has one of the most complex research-performance-assessment systems in the world. It involves domestic assessment and audit of R&D organizations and two independent external evaluations of all Japanese universities, research organizations and units that are part of national university corporations [3]. The assessment involves the analysis of quantitative organizational indicators, such as the number of scientific papers and monographs, patent applications and patents granted, inventions, grants and joint projects, as

[1] For more details, see the official website of the Research Evaluation Framework www.ref.ak.uk, Panel Criteria and Working Methods.

well as expert review of the quality of the results (the scientific value, as well as social, economic, and cultural effects).

Research is evaluated in the United States, Canada, Italy, Sweden and other countries in Europe and worldwide. The implementation of such assessment systems is often part of development mechanisms that propel economic growth and structural diversification. In view of the absolute growth of public expenditures, growing requirements to R&D performance, and weakening control over the use of public funds, assessment instruments are continuously improved and new quality standards are codified to adapt to new realities.

The importance of research-performance assessment and a shift to a new performance-based model of research funding has been debated in Russian since the mid-2000s. The first specific actions to implement this practice in the Russian research context also date back to the mid-2000s. In 2006–2007, the federal executive bodies led by the Russian Ministry of Economic Development conducted the assessment of their subordinate public research centers.

The subsequent phase of the research-assessment approach developed in Russia involved the design of a methodology applied to calculate the personal research performance (PRP)[2] coefficient and the implementation of the first monitoring stage on its basis (2006–2007)[3]. In 2009–2011, a series of official documents stipulating the activity of research-performance assessment committees, as well as the related assessment methods and administrative regulations, was adopted. During and after this period, several public agencies and state corporations evaluated the performance of their subordinate scientific and technological centers. However, this assessment did not result in any significant institutional changes. Although the research performance was on average quite low during this period and in some cases even negative, the responsible agencies failed to criticise the activities carried out by their subordinate organizations and improve the structure of the research networks in Russia.

In 2013, a decision was made to move to a second stage of monitoring and assessment based on the Russian Government Decree no. 979 of 1 November 2013. The stage was marked by the development of a system for the annual monitoring and 5-year assessment of activities pursued by research organization involved in civil R&D. The key assessment tools included clustering of research organizations in comparable reference groups and defining thresholds for the related performance indicators. The structure of reference groups, as well as the composition of the main and additional performance indicators, were approved in the minutes of the meeting of the interagency commission on performance assessment no. DL-2/14pr of January 14, 2016. According to this protocol, the assessment must be organized for 39 research areas and three scientific profiles corresponding to various types of results. While validated in practice, the proposed approach raised a number of issues related to the possibility of calculating individual indicators, populating the reference groups with a sufficient number of organizations, and addressing the performance of interdisciplinary organizations. The aim of this paper is to present an alternative experimental combinatorial model for the distribution of organizations by reference groups in line with their profile and area of activity. The goal is also to present an algorithm to define various performance categories based on a set of quantitative scientometric indicators.

Methods of Analysis and Data Sources

The analysis is based on the information retrieved from the federal performance monitoring system for scientific organizations that carry out R&D and technological work as of September 5, 2017. At this point, the system included information on 1795 organizations, of which 1502 organization with complete profiles. To ensure relative consistency, only scientific organizations with non-zero R&D expenditures and non-zero number of researchers were selected for further analysis. The final sample contained 1018 items. The algorithm for the development of reference groups and the definition of performance categories consisted of the following steps.

1. *The distribution of scientific organizations* by groups in twelve key research areas in line with the Unified Science Classifier developed by the Public Research Control Committee and harmonized at the aggregate level with OECD Fields of Science Classification. Organizations were grouped by experts based on the information on the research areas provided by scientific organizations. The reduction in the number of research areas relied on the best foreign practices (specifically, the Italian exprience described in studies [4, 5]), on the one hand, and on the need to increase the agility of the model, on the other.

2. *The definition of research profiles* (hereinafter, the profile) for each area depending on their focus on a specific type of scientific results, identified by using the following indicators.

A. The number of scientific publications indexed in the Web of Science, per 100 researchers.

[2] Approved by the Joint Order of the Russian Ministry of Education and Science, the Russian Ministry of Healthcare and Social Development, and the Russian Academy of Sciences No. 273/745/68 "On the approval of the procedure and conditions for the use of incentive payments to increase the performance of scientists and managers employed by research organizations and research centers of the Russian Academy of Sciences" of November 3, 2006.

[3] This work has framed the national assessment system, which was launched following the adoption of the Russian Government Decree no. 312 of April 8, 2009 "On the assessment of the performance of research organizations...".

This indicator differs from that proposed by the Russian Ministry of Education and Science, as it ensures greater accuracy and verifiability of data. In addition, this indicator equates the chances of all organizations to be represented in the system due to the fact that further calculations are correlated with the research area of the organization.

B. The number publicly recorded or legally protected in Russia or abroad intellectual property rights, as well as the number of design and technological documentation per 100 researchers.

C. The ratio of the volume of the performed work, services provided (R&D, scientific and technological services, income earned from the use of intellectual property) and the total number of R&D employees (in thousands of rubles).

To reduce the scale effect, each indicator (A–C) reflecting a certain type of results was normalized by dividing by the number of employees involved in the achievement of the result. Financial results require the involvement of various categories of research personnel, whereas researchers tend to be the main "producers" of scientific publications and technologies.

The organization was assigned a specific profile based on the expressed value of the indicator (A–C), which is not equal to zero and not lower than the corresponding median value for the organizations assigned to the same research area. This approach allowed us to identify four profiles:

I. "Knowledge generation" (indicator A is expressed);

II. "Technological development" (indicator B is expressed);

III. "Scientific and technological services" (indicator C is expressed);

IV. "Special" (none of the indicators A–C is expressed).

The intersection of the research profiles for each of the 12 research areas forms a reference group. It is assumed that one organization can have from one to three activity profiles, that is, be part of several reference groups, while belonging to the same research area.

3. *Performance thresholds* are calculated for the reference groups as the median values of the corresponding performance indicators averaged over 5 years (the average indicator is established as the ratio of the corresponding numerators and denominators summarized over five years) for the scientific organizations of this reference group. Data for 1 year (2016) was used in the experimental calculations.

4. *The performance category* is established for the organization in the reference group according to the following rule:

• The organization in the reference group belongs to the first performance category, if the value of the expressed indicator for its profile is non-zero and not lower than the median value of the respective indicator in the related research area, increased by 25%;

• The organization in the reference group belongs to the third performance category, if the value of the expressed indicator for its profile is not higher than the median value of the respective indicator in the related research area, reduced by 25%;

• The organization in the reference group belongs to the second performance category, if it is not assigned to the first or the third performance category in this reference group.

This approach allows us to assign different performance categories to organizations considering all of its profiles in the same research area. As a result, it is possible to establish the leading organizational activity profiles (knowledge generation, technological development, or provision of scientific and technological services) and to define where the organization demonstrates satisfactory scientific results and where research is no longer the main organizational activity.

Based on the aforementioned rules, we performed a series of test calculations. The results are presented in Table 1 and Table 2.

The Results of Test Calculations

Four research profiles were identified for the obtained sample of organizations in 12 fields of science. As a result, the reference groups were sufficiently populated (except for the group of other natural sciences (Table 1). Each research profile is characterized by a unique mix of resources and results, where different evaluation criteria and threshold values are used.

Several profiles are degenerated. As an example, there are practically no organizations with protected intellectual property rights in humanities. In contrast, this group is rather well expressed for technical, medical and agricultural sciences. Similar imbalances can be observed in other areas.

Table 2 shows that the median values of the indicators are higher for the organizations with the dominant profiles (indicators). In addition, similar to the composition of the reference groups, differences can be observed for various research areas. Thus, the highest and the lowest levels of publication activity per 100 researchers (the indicator A corresponding to the "knowledge generation" profile) can be observed in mathematics and in agricultural sciences, respectively. The median values of the indicator B, which primarily defines the performance of applied sciences, are highest for the organizations of the technical profile, as well as for exact sciences (the high value of the indicator in the latter case may also be due to the insufficient population of this area). Finally, the indicator C, which defines the total volume of R&D as well as scientific and technological services performed, is highest for Physics, as well as for other Natural Sciences.

Table 1. The results of the modeled composition of reference groups

Field of science	Category	Total	Including by profiles			
			I	II	III	IV
Medical Sciences and Public Health	Total	158	79	79	79	20
	1st category		28	17	17	
	2nd category		41	51	58	
	3rd category		10	11	4	
Agricultural Sciences	Total	232	97	116	116	44
	1st category		30	25	29	
	2nd category		54	77	85	
	3rd category		13	14	2	
Social Sciences	Total	80	40	30	40	13
	1st category		11	7	8	
	2nd category		26	17	30	
	3rd category		3	6	2	
Engineering and Technology	Total	202	101	101	101	25
	1st category		31	22	25	
	2nd category		58	66	72	
	3rd category		12	13	4	
Humanities	Total	38	19	16	19	7
	1st category		7	1	5	
	2nd category		11	13	14	
	3rd category		1	2	0	
Life Science	Total	184	92	92	92	26
	1st category		31	20	21	
	2nd category		53	64	65	
	3rd category		8	8	6	
Computer and Information Sciences	Total	61	31	31	31	9
	1st category		13	7	7	
	2nd category		10	17	21	
	3rd category		8	7	3	
Mathematics	Total	25	13	13	13	4
	1st category		3	4	2	
	2nd category		9	9	10	
	3rd category		1	0	1	
Earth Sciences and Environmental sciences	Total	117	59	59	59	16
	1st category		17	15	12	
	2nd category		38	35	45	
	3rd category		4	9	2	
Other Natural and Exact sciences	Total	16	8	8	8	3
	1st category		2	4	2	
	2nd category		4	1	5	
	3rd category		2	3	1	
Physics and Astronomy	Total	58	29	29	29	6
	1st category		9	9	8	
	2nd category		17	17	20	
	3rd category		3	3	1	
Chemical Sciences	Total	37	19	19	19	3
	1st category		5	5	4	
	2nd category		12	10	15	
	3rd category		2	4	0	

Table 2. The median performance indicator values of the reference groups

Field of science	Total			Including by profiles											
	A	B	C	A				B				C			
				I	II	III	IV	I	II	III	IV	I	II	III	IV
0	9.09	6.55	585.64												
1	21.54	6.62	743.32	41.79	21.85	21.43	3.78	6.67	17.43	6.12	2.54	740.01	740.80	1 173.13	426.76
2	0.00	8.09	488.30	5.45	0.00	1.37	0.00	8.11	20.80	8.92	0.00	550.47	512.26	676.34	336.40
3	4.58	0.00	763.62	11.42	4.82	4.77	0.00	0.00	9.39	0.00	0.00	805.91	747.10	1 149.30	537.70
4	2.57	12.11	922.52	24.71	2.76	1.57	0.00	12.24	33.33	16.87	1.66	904.18	1 078.62	1 764.26	338.52
5	8.74	0.00	655.48	18.12	8.78	13.92	0.00	0.00	10.49	1.00	0.00	760.11	768.15	872.03	460.75
6	14.93	4.07	730.12	44.29	15.45	26.54	1.58	4.00	11.82	3.56	1.67	855.05	704.69	1 109.35	453.10
7	7.43	4.08	1 018.97	59.50	34.69	9.51	0.00	8.55	13.46	4.00	0.00	1 018.97	952.70	1 517.46	415.28
8	63.01	9.68	918.10	98.73	75.71	72.73	6.48	10.39	13.46	9.94	3.36	1 147.40	1 034.03	1 321.03	476.48
9	18.93	3.38	832.39	43.33	15.00	22.86	5.52	2.51	9.94	4.17	0.00	903.77	1 034.69	1 371.91	545.43
10	5.13	7.37	1 257.30	13.43	9.18	11.76	0.00	33.41	41.49	6.65	2.27	1 402.10	1 257.30	2 401.11	924.11
11	41.85	6.73	1 057.55	80.04	26.98	30.72	5.00	4.35	19.29	10.78	2.85	1 034.69	1 221.67	1 946.73	580.32
12	42.59	6.25	994.18	94.39	34.86	65.24	13.51	5.78	15.32	5.78	4.05	1 079.85	943.45	1 222.34	674.64

Legend for the field of science: (0) For all organizations, (1) Medical Sciences and Public Health, (2) Agricultural Sciences, (3) Social Sciences, (4) Engineering and technology, (5) Humanities, (6) Life Sciences, (7) Computer and Information Sciences, (8) Mathematics, (9) Earth Sciences and Environmental Sciences, (10) Other Natural and Exact Sciences, (11) Physics and Astronomy, (12) Chemical Sciences.

CONCLUSIONS

The proposed approach for the formation of reference groups and the quantitative assessment of scientific and technological performance can be applied to various samples provided they contain similar types of organizations and it is possible to clearly define fields of science (at medium and high levels of aggregation). In addition, the proposed model allows one to consider different types of results and establish different types of leaders depending on the organizational profiles, thus enabling the possibility of compiling alternative rankings.

Despite the aforementioned advantages, the proposed approach has several limitations that need to be taken into account in further analysis. Thus, the results of the described distribution are largely defined based on the threshold values established for each reference group. Changing these values can lead to significant changes in the entire analysis, since the threshold values depend on the behavior of all scientific organizations in the sample at the point in time. Accordingly, any change in the composition of the sample may affect the evaluation of a given organization. Such changes can be both productive (for example, the growing performance indicators of some organizations can objectively worsen the situation for others over time) or counterproductive (for example, by including the unusual items into the sample, for which the proposed indicators will not produce strong effects or, on the contrary, will not have any expressed values).

The proposed approach does not support any further differentiation of scientific and technological results by fields of science or any performance evaluation of multidisciplinary organizations. This limitation remains a systemic constraint; therefore, further study may focus on the development of methods to verify scientometric data and apply fractional count to obtain more accurate values.

Finally, the use of standardized indicators leads to a situation where large scientific research institutes may come up short of medium-sized and small organizations due to the large scale of their activities. As a result, their contribution is underestimated. The introduction of additional indicators corresponding to the size of organizations (large, medium-sized and small) could solve this methodological shortcoming.

In conclusion, it should be noted that the proposed combinatorial model is to some extent declarative and should only be used as a method for stratification and preliminary assessment of the organizational scientific and technological performance. It is important to conduct an independent expert review taking qualitative characteristics (e.g., the value) of individual results into account. Further studies will focus on overcoming the described limitations and optimizing the solutions.

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