Measuring spatial effects based on a knowledge production function

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In the fourth industrial revolution[1], human capital, as a stock of produced knowledge, is becoming a key factor in sustainable economic growth, human-centered technologies are a major direction in leading management practices, and the digital divide and the convergence of knowledge production across regions and countries are becoming a new factor of economic and social inequality. In 2020 in Russia 60% of digital technologies were in finance, transport, energy and healthcare[2], 69 constituent entities accounted for a fifth of all patent claims for inventions in digital technologies[3]. We took the idea of the study from an article by Professor Zvi Griliches «Issues in assessing the contribution of research and development to productivity growth». In the article, the author proposed to include a measure of the current state of technological knowledge in the production function that links output with traditional resources, such as labor and capital. To measure technological knowledge, the author used the number of granted patents in relation to current and past spending on research and development. This approach marked the beginning of the use of the production function of knowledge in science.

In the middle of the 20th century, Simon Kuznets wrote the following about the vital importance of technology: "It can be said that since the second half of the 19th century, science-based technologies have definitely become the most important source of economic growth in developed countries - in the electric power industry, the production of internal combustion engines, the production of electronic equipment, nuclear technology, biotechnology.[4]» Contrary to Robert Solow's model of capital accumulation and slowing growth, since the middle of the 20th century there has been an acceleration in the average growth rate of the world economy, in part because technological change overcomes the limiting effects of accumulation due to its transversality and the rise in the cost of production factors. What has accelerated technological change?

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[1] Schwab K. The Fourth Industrial Revolution. - M .: Eksmo, 2016.
[2] Digitalization for humans: "What we are doing now is comparable to the conquest of space." ISSEK HSE University. URL: https://issek.hse.ru/news/463373122.html
[3] Involving regions in the development of digital technologies. ISSEK HSE University. URL: https://issek.hse.ru/news/513322514.html
[4] Kuznets, S. Modern economic growth. New Haven: Yale University Press, 1966.

At the end of the 20th century, Paul Romer proposed a model that emphasized the external effect of knowledge accumulation on factor productivity growth through the accumulation and exchange of internal knowledge through investment.[5] Robert Lucas has shown that an economy in which the rate of accumulation is proportional to the stock of infinitely expanding human capital grows in the long run at a rate that exceeds the rate of technological progress, and the "technology" of human capital production determines the rate of economic growth. Later Paul Romer [6] emphasized patent-protected innovations, when innovators gain monopoly power to increase profits. Knowledge that cannot be kept as a trade secret becomes available to other market participants, and higher quality products crowd out lower quality ones, and disruptive technologies give rise to a reorganization of jobs. At the beginning of the 21st century, the concepts of sustainable development and the digital economy received a lot of attention. The economic component of the concept of sustainable development implies ensuring the well-being and resources of future generations while meeting the needs of current generations.[7] Among the sustainable development goals of the UN are such as: promoting economic growth, industrialization and innovation, full and productive employment, reducing inequality within and between countries, ensuring rational patterns of consumption and production.

A review of growth theories allows us to highlight the main theoretical prerequisites for economic transformation and new growth opportunities due to digitalization.

First, through networking, datification, algorithmization and platformization, technological change overcomes the limiting effects of accumulation and accelerates the average growth rate of the economy. An increase in the stock of internal knowledge indirectly builds up world experience, increases the productivity of factors, and creates an external effect of knowledge accumulation.

Secondly, human capital as a set of skills receives a powerful impetus to their endless expansion and, in the long term, to economic growth at a rate that exceeds the rate of technological progress. Thanks to platform business models, the “technology” of human capital production is being transformed.

Third, technological change increases the accumulation of knowledge and innovation. Their non-competitiveness and availability lead to equalization of prices for factors of production and convergence of growth rates. Platform solutions as "technologies of wide application" generate the reorganization of jobs and the replacement of labor with capital, tracking any changes in economic entities, the commercialization of public life and the global integration of institutions and companies. Innovators - owners of digital platforms, with monopoly power, increase profits and the digital divide.

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[5] Romer P. Increasing returns and long-run growth. Journal of Political Economy, 1986, vol. 94, pp.1002-1037.
[6] Romer P. Endogenous. Technological Change. Journal of political economy, 1990, vol. 98, pp. 71-102.
[7] Brundtland, G. Our Common Future, World Commission on Environment and Development (WCED), United Nations. 1987.

The production function of knowledge appears to be an adequate approach for modeling connections in the digital economy[8]. An important consequence of the relationship between the diffusion of technology as a product of knowledge and sustainable growth is the convergence of its rates[9]. Endogenous growth theory and empirical evidence recognize that space is critical to knowledge diffusion and innovation[10]. Therefore, **research questions** are of interest: Is there a long-term convergence of knowledge production in the regions? What is the impact of human capital and digitalization on knowledge production, taking into account their interregional interaction? **Research hypothesis**: the impact of human capital and digitalization on knowledge production is not the same, both directly (within regions) and indirectly (in neighboring regions).

Model. The production function of knowledge[11] has been modified with temporal and spatial lags. Dependent variable are the average growth rate of issued patents for inventions and utility models per 10 thousand population. Independent variables are the number of research and development personnel per 10 thousand population; internal costs of R&D per capita, thousand rubles; use of the Internet in organizations, %; expenditures for the introduction and use of digital technologies per capita, thousand rubles; expenditures for technological innovation per capita, thousand rubles (as a proxy of technology development); fertility rate, % (as a proxy of the social environment). A sample of data was obtained on the official website of the Federal state statistics service of the Russian Federation (www.gks.ru) for 83 regions for the period from 2014 to 2019. In the R software environment, the Moran and Geary indices were estimated and models of conditional β-convergence were built on panel data by the SAR, SDM, SEM types[12]:

$$\frac{1}{T}\ln\frac{y_{it_{0+T}}}{y_{it_0}} = \alpha_i + \beta\ln y_{it_0} + \sum_{k=1}^{K}\gamma_k \ln X_{kit-2} + \rho W_{ij}\ln\frac{y_{it_{0+T}}}{y_{it_0}} + \varepsilon_{i,t_{0+T}}$$

$$\frac{1}{T}\ln\frac{y_{it_{0+T}}}{y_{it_0}} = \alpha_i + \beta\ln y_{it_0} + \sum_{k=1}^{K}\gamma_k \ln X_{kit-2} + \sum_{k=1}^{K}\theta_k W_{ij}\ln X_{kit-2} + \rho W_{ij}\ln\frac{y_{it_{0+T}}}{y_{it_0}} + \varepsilon_{i,t_{0+T}}$$

$$\frac{1}{T}\ln\frac{y_{it_0+T}}{y_{it_0}} = \alpha_i + \beta\ln y_{it_0} + \sum_{k=1}^{K}\gamma_k \ln X_{kit-2} + \lambda W u_{i,t_0+T} + \varepsilon_{i,t_0+T}$$

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[8] Griliches Z. Issues in assessing the contribution of research and development to productivity growth. The Bell Journal of Economics. 1979.Vol.10. P. 92–116.
Pakes A., Griliches Z. Patents and R&D at the firm level: A first look. R&D, Patents, and Productivity. Chicago: University of Chicago Press. 1984. P. 55–72.

[9] Barro R. Economic growth / R. J. Barro, H. Sala-i-Martin. –M .: Binom. Knowledge laboratory. 2014.

[10] Krugman, P.. The role of geography in economic development. International Regional Science Review. 1999. Vol. 22 (2). P. 142–161.
Fritsch M, Franke G. Innovation, regional knowledge spillovers and R&D cooperation. Research Policy. 2004. Vol. 33. P. 245–255.

[11] Barro, R., Sala-i-Martin, X. Convergence. The Journal of Political Economy. 1992. Vol. 100 (2). P. 223–251.
Rey S J., Montouri B.D. US Regional Income Convergence: A Spatial Econometric Perspective. Regional Studies, 1999. Vol. 33(2). P. 143 – 156.

[12] Elhorst, J. Spatial Econometrics. From Cross-Sectional Data to Spatial Panels. Springer. 2014.

where $i = 1, \ldots 79$ is the number of the region, $[t_0 + T]$ is the convergence period from 2014 to 2019, $y_{i,t0}$ is the number of issued patents in 2014, β is the convergence parameter, γ_k - estimated parameters for independent variables; W_{ij} is inverse distance weighting, ρ, λ is a spatial coefficients, $\varepsilon_{i,t0+T}$ is a random error with a normal distribution.

Results. The study measured the linear correlation coefficient between the ICT development index and gross domestic product per employed person.

Table 1[13] - Linear correlation coefficient between ICT development index and gross domestic product per employed person

The developed countries	Countries with economies in transition	Developing countries
Average value of the ICT development index in 2017		
8,08	6,57	4,15
Linear coefficient of simple correlation between the ICT development index and GDP per 1 employed		
0,28	0,53	0,73

It turned out to be 2.6 times higher for developing countries than for developed ones.

The COVID-19 pandemic has caused a powerful acceleration in the use of digital tools and ways of digitalization. In Russia, the expenses of organizations for the purchase of digital equipment (by 1.5 times), digital content (by 3 times), and staff training (by 4 times) have increased. The daily audience of the Russian Internet has reached almost 77% of the adult population.[14] The number of users of electronic public services has increased. The presence of fixed broadband access to the Internet in the sectors of the economy increases the use of cloud services and digital platforms. Higher education, health care, information technology production, and the financial sector are leading here. The "contactless" economy has strengthened.[15]

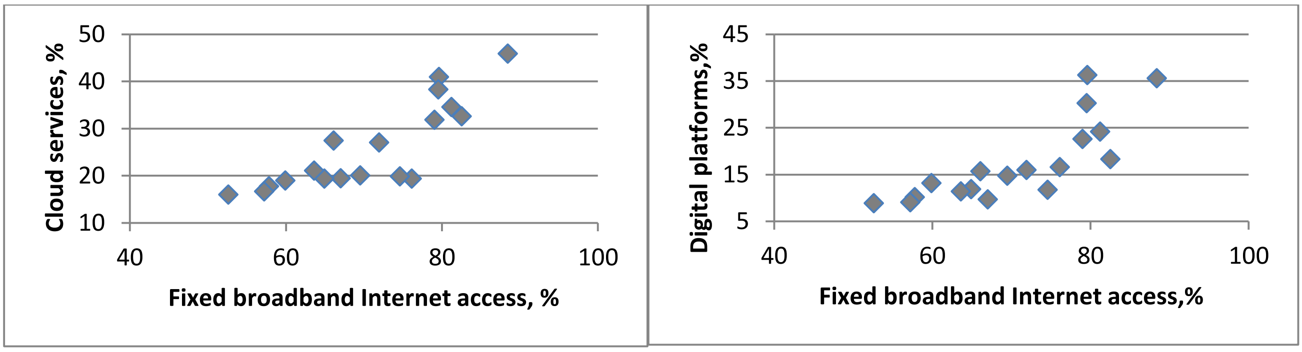

Fig. 1. Correlation field between the fixed broadband Internet access and cloud services / digital platforms in organizations in 2020. Source: obtained by the authors according to the collection "Digital Economy: 2022"

[13] Received by the authors based on materials from the collection “Russia and the World. 2020 ". – Moscow, Rosstat. 2020.

[14] Digital Economy: 2022: A Brief Statistical Collection. Moscow. NRU HSE, 2022. – 124 p.

15 Technologies against the pandemic: new business models and services. 06.10.2021. ISSEK NRU HSE. https://issek.hse.ru/mirror/pubs/share/513915566.pdf

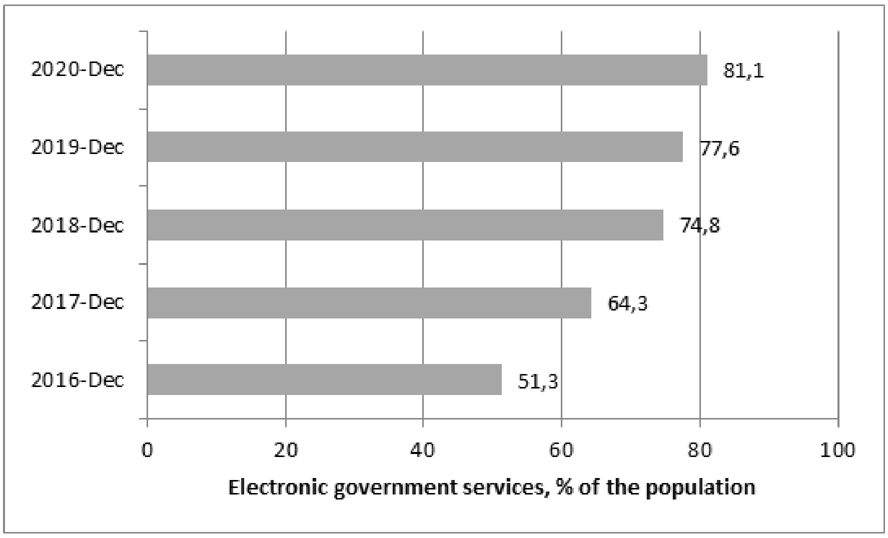

Fig. 2. Receiving electronic state and municipal services by the population. Source: obtained by the authors according to the collection "Digital Economy: 2022“. Moscow, HSE University. 2020.

The Moran and Geary Global Indices found that strong regions contribute to the growth of human capital and the production of knowledge from their neighbors.

Table 2 - Moran’s and Geary’s Indices for the number of granted patents for inventions and utility models per 10 thousand population

Indices	2012	2013	2014	2015	2016	2017	2018	2019
Moran	0,15**	0,16***	0,19***	0,17***	0,15***	0,20***	0,27***	0,63***
Geary	0,55**	0,65***	0,58***	0,66***	0,58***	0,63***	0,58***	0.63***

Source: obtained by the authors according to the collection «Regions of Russia. Socio-economic indicators. 2021».

The Moran and Geary Global Indices found that strong regions contribute to the growth of human capital and the production of knowledge from their neighbors. As technological innovation is concentrated in strong regions with a high concentration of factors of production[16], this could predict a technological breakthrough thanks to the leading regions. Moran's charts from 2012 to 2019 showed the concentration of most regions in the LL quadrant.

[16] Bagautdinova N, Kadochnikova E., Technological innovations: Analysis of short-term spatial effects in regions by development of econometric model//Industrial Engineering and Management Systems. - 2020. - Vol.19, Is.4. - pp.888-895

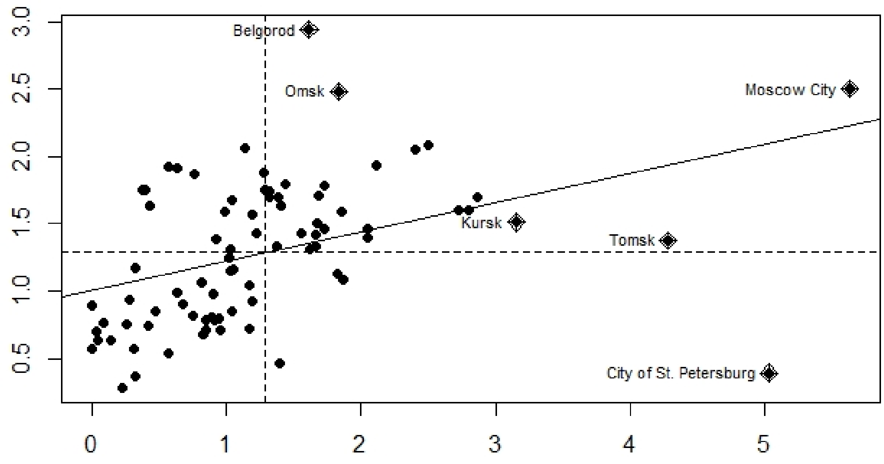

Fig. 3. Moran's chart of the number of patents granted per 10,000 population in 2019.

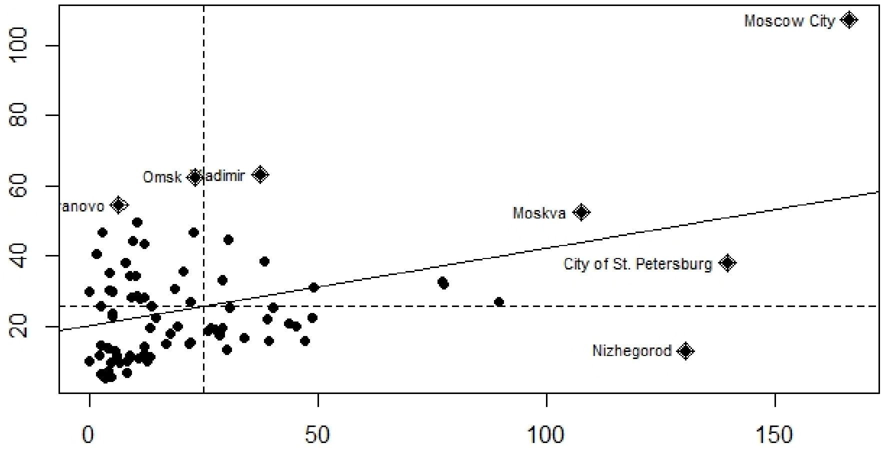

Fig. 4. Moran's chart of the R&D per 10,000 population in 2019.

Local Moran's indices indicated the concentration of human capital and the number of issued patents in Moscow, the Moscow Region, St. Petersburg, and the Siberian Federal District.

Fig. 5. Cartogram of the number of personnel engaged in R&D per 10,000 population in 2019.

Fig. 6. Cartogram of the number of issued patents for inventions and utility models per 10,000 population in 2019.

Table 3 shows that the found β-convergence indicates an increase in knowledge production in weak regions. As expected, the positive impact of human capital, internal costs of R&D per capita, expenditures for technological innovation per capita was confirmed. Positive significant spatial coefficients (p) and (λ) affirm the assumption of regional cooperation and the impact of shocks from neighboring regions on the growth of knowledge production in this region. Spatial interactions of the number of personnel engaged in R&D and the internal costs of R&D with the dependent variable were found.

Table 3 - Regression results of the average growth rate of issued patents for inventions and utility models per 10,000 population

Regressors	***SEM_RE***	***SAR_RE***	***SDM_RE***	***SEM _ FE***	***SAR_ FE***	***SDM_FE***
Intercept	0.951 (0.666)	0.932 (0.670)	1.321 (1.445)			
Natural logarithm of the number of granted patents in 2014	-0.108*** (0.016)	-0.106*** (0.016)	-0.105*** (0.016)			
The number of research and development personnel per 10 thousand population	0.019 (0.032)	0.014 (0.032)	0.027 (0.032)	0.118* (0.049)	0.107* (0.050)	0.070* (0.054)
Internal costs of R&D per capita	0.028 (0.028)	0.034 (0.028)	0.019 (0.028)	0.058 (0.036)	0.066* (0.036)	0.067 (0.037)
Use of the Internet in organizations	-0.193 (0.142)	-0.188 (0.144)	-0.213 (0.143)	-0.172 (0.159)	-0.165 (0.161)	-0.171 (0.159)
Expenditures for the introduction and use of digital technologies per capita	-0.013 (0.013)	-0.013 (0.013)	-0.015 (0.014)	-0.028* (0.016)	-0.027* (0.016)	-0.027 (0.016)
Expenditures for technological innovation per capita	-0.003 (0.006)	-0.003 (0.006)	-0.008 (0.007)	-0.014* (0.008)	-0.015* (0.008)	-0.022* (0.009)
Fertility rate	-0.056 (0.072)	-0.051 (0.065)	0.158 (0.101)	0.051 (0.122)	0.039 (0.096)	0.460* (0.257)
Spatial autoregression coefficient for the dependent variable		0.208** (0.064)	0.231*** (0.065)		0.286*** (0.060)	

Spatial autoregression coefficient for the shock	0.276*** (0.070)			0.292*** (0.061)		
Slag (Natural logarithm of the number of granted patents in 2014)			0.060* (0.030)			
Slag(The number of research and development personnel per 10 thousand population)			-0.086 (0.053)			-0.338** (0.054)
…						
Slag (Fertility rate)			-0.274* (0.121)			-0.335 (0.257)
Hausman test (p-value)	0.009	0.010	1.275e-05			
n	332	332	332	332	332	332

Source: obtained by the authors according to the collection «Regions of Russia. Socio-economic indicators. 2020».

Table 4 shows that the direct effects (effects within the region) affirmed the positive impact of human capital, internal costs of R&D and the cost of technological innovation on the knowledge production in the region. Significant indirect effects, i.e. the impacts of neighbors indicate the positive effect of internal costs of R&D. Significant direct and indirect effects of digitalization have not been identified. Perhaps this is due to the fact that the share of the ICT sector in Russia's gross value added is less than 3% [17], a quarter of the adult population do not have digital skills, about 40% of our fellow citizens have only basic digital skills[18]. Overall, it's too early to talk about digital abundance [19].

Table 4 - Direct and indirect spatial effects

Regressors	Direct	Indirect	Total
Natural logarithm of the number of granted patents in 2014	-0.201** (0.095)	0.077 (0.084)	-0.124*** (0.014)
The number of research and development personnel per 10 thousand population	0.030 (0.064)	-0.011 (0.036)	0.019 (0.031)
Internal costs of R&D per capita	0.032 (0.061)	-0.012 (0.035)	0.020 (0.029)
Use of the Internet in organizations	-0.510 (0.353)	0.197 (0.247)	-0.313** (0.147)
Expenditures for the introduction and use of digital technologies per capita	-0.0004 (0.032)	0.0001 (0.017)	-0.0003 (0.016)
Expenditures for technological innovation per capita	-0.012 (0.015)	0.004 (0.008)	-0.008 (0.007)
Fertility rate	0.212 (0.179)	-0.082 (0.115)	0.130 (0.083)
Slag (Natural logarithm of the number of granted patents in 2014)	0.081 (0.056)	-0.031 (0.038)	0.050** (0.024)
Slag (The number of research and development personnel per 10 thousand population)	-0.112 (0.110)	0.043 (0.066)	-0.069 (0.056)

[17] Indicators of the digital economy: 2020: statistical collection. - M .: HSE University, 2020.

[18] How Russians are settling in the new digital world. ISSEK HSE University. URL: https://issek.hse.ru/news/461512008.html

[19] Bagautdinova N.G. On the question of the mechanisms of the "resource curse" in the digital economy. V International Economic Symposium. St. Petersburg, 2021. P. 164-170.
Kadochnikova E. I., Bagautdinova N. G. The "Resource Curse" in the Digital Economy: an Econometric Assessment. The 68th North America Meetings of the Regional Science Association International, Denver, NARSC, 2021.

…			
Slag (Fertility rate)	-0.659** (0.350)	0.254 (0.280)	-0.404*** (0.113)

Source: obtained by the authors according to the collection «Regions of Russia. Socio-economic indicators. 2020».

Conclusions. A closer correlation of digital resources with the gross domestic product was found for a group of developing countries, which doesn't contradict theoretical judgments about the impact of the technology spread on the β-convergence of economic growth. The found β-convergence indicates an increase in knowledge production in weak regions. The positive impact of human capital, internal costs of R&D per capita, expenditures for technological innovation per capita was confirmed. The assumption of regional cooperation and the impact of shocks from neighboring regions on the growth of knowledge production in this region was confirmed. Spatial interactions of the number of personnel engaged in R&D and the internal costs of R&D with the dependent variable were found. The assumption about the significant positive impact of digitalization on the production of knowledge in the regions was not confirmed.

The β-convergence of the average growth rates of knowledge production and their spatial dependence under conditions when many regions have little human capital and patenting, can confirm the diffusion of technologies through their copying from the leading regions, which is cheaper than the invention of new ones. Regions that are technology followers attract external investment, gradually catch up with technology leaders and promote the convergence of knowledge production growth. With the market turbulence, large producers and economies with higher savings rates have greater growth potential and sustainable development opportunities. Digital innovations in the economy are becoming a key factor in ensuring the well-being and resources of future generations as an economic component of the concept of sustainable development.

Research novelty. The novelty of the study lies in measuring the convergence of the average growth rates of knowledge production in the regions, taking into account spatial interactions. The results can be used by authorities and other institutions in managing the transformation of economic and social sectors through the introduction of digital technologies and platform solutions, in providing training in accordance with the goals of the National Project "Digital Economy".