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REGIONAL DIGITAL INFRASTRUCTURE: KEY ELEMENTS AND THEIR INTERRELATIONS

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Abstract. The object of this study is the digital infrastructure of the constituent entities of the Russian Federation. The subject of the study is the structural interrelations between the elements of digital infrastructure within the regional context. The methodological framework comprises a systems approach to analyzing infrastructure as a multilevel phenomenon, a comparative analysis of statistical data from the Ministry of Digital Development of the Russian Federation for 2022–2023, and a case study method for an in-depth examination of practices in three types of regions: a metropolitan region (Moscow), a digitalization leader (Tatarstan), and a typical agrarian region (Kursk Oblast). The study reveals a persistent differentiation among regions in terms of digital infrastructure development: the gap between the most and least developed entities in network capacity reaches a factor of 4.7. Three groups of systemic problems hindering effective interaction among infrastructure elements are identified: economic (the cost of laying fiber-optic communication lines in rural areas reaches RUB 2.8 million/km), technological (63% of regional information systems use foreign software), and human capital (an annual outflow of 18.7% of IT specialists from regions). It is established that sanctions pressure has accelerated import substitution (the share of domestic software in the public sector increased from 35% to 65%) but has led to delays in the implementation of infrastructure projects in 40% of regions. Practical recommendations are developed for federal authorities, regional governments, and the business community aimed at optimizing the architecture of digital infrastructure, taking into account the specific characteristics of different types of regions. An integrative model of regional digital infrastructure is proposed, encompassing structural, spatial, institutional, and technological sovereignty components.

Keywords: digital infrastructure, enterprise architecture, regional development, technological sovereignty, systems analysis, spatial economics, import substitution, human capital potential, digital transformation

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АРХИТЕКТУРА ЦИФРОВОЙ ИНФРАСТРУКТУРЫ РЕГИОНА: КЛЮЧЕВЫЕ ЭЛЕМЕНТЫ И ИХ ВЗАИМОСВЯЗИ

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Аннотация. Объектом исследования выступает цифровая инфраструктура регионов Российской Федерации. Предметом исследования являются структурные взаимосвязи между элементами цифровой инфраструктуры в региональном контексте. Методологическую основу составили системный подход к анализу инфраструктуры как многоуровневого явления, сравнительный анализ статистических данных Министерства цифрового развития РФ за 2022-2023 годы, а также метод кейс-стади для углубленного изучения практик трех типов регионов: столичного (Москва), лидирующего в цифровизации (Татарстан) и типичного аграрного региона (Курская область). В результате исследования выявлена устойчивая дифференциация регионов по уровню развития цифровой инфраструктуры: разрыв между наиболее и наименее развитыми субъектами по показателю пропускной способности сетей достигает 4,7 раза. Определены три группы системных проблем, препятствующих эффективному взаимодействию элементов инфраструктуры: экономические (стоимость прокладки ВОЛС в сельской местности достигает 2,8 млн руб./км), технологические (63% региональных информационных систем используют иностранное ПО) и кадровые (ежегодный отток 18,7% IT-специалистов из регионов). Установлено, что санкционное давление ускорило импортозамещение (доля отечественного ПО в госсекторе выросла с 35% до 65%), но привело к задержкам в реализации инфраструктурных проектов в 40% регионов. Разработаны практические рекомендации для федерального центра, региональных органов власти и бизнес-сообщества, направленные на оптимизацию архитектуры цифровой инфраструктуры с учетом специфики различных типов регионов. Предложена интегративная модель региональной цифровой инфраструктуры, включающая структурный, пространственный, институциональный компоненты и компонент технологического суверенитета.

Ключевые слова: цифровая инфраструктура, архитектура предприятия, региональное развитие, цифровое неравенство, технологический суверенитет, системный анализ, пространственная экономика, импортозамещение, кадровый потенциал, цифровая трансформация

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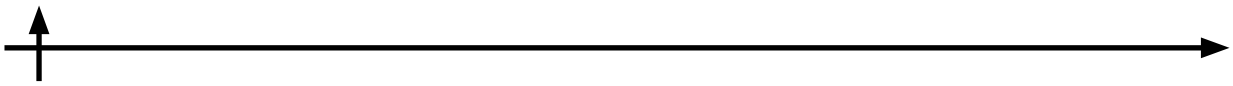
Introduction

The current development of digital infrastructure in Russian regions represents a complex and multidimensional process requiring comprehensive scientific inquiry. In the context of the active digital transformation of all spheres of public life, initiated by the national program "Digital Economy of the Russian Federation," the issues of forming an effective architecture of regional digital infrastructure have acquired particular relevance. The state program adopted



in 2017 set the vector for the country's technological development (Decree No. 1632-r of July 28, 2017). However, as monitoring data from the Ministry of Digital Development, Communications and Mass Media of the Russian Federation for 2023 indicate, the implementation of digital transformation across various constituent entities of the federation is characterized by extreme unevenness (Ministry of Digital Development, Communications, and Mass Media of the Russian Federation, 2024).

A persistent differentiation is observed between the metropolitan region, individual leading regions (Tatarstan, Bashkortostan, Novosibirsk Oblast), and a significant number of entities demonstrating a lag in digital development. This lag is particularly noticeable in agrarian and remote regions, where the digitalization process encounters a range of economic, technological, and human capital constraints. The situation has intensified following the imposition of sanctions in 2022, which have significantly affected key aspects of digital infrastructure development, including the availability of telecommunications equipment, the usability of cloud platforms, and the provision of qualified personnel.

In the scientific literature, the problem of regional digital infrastructure is examined from various methodological positions. The technocratic approach focuses on the technical parameters of infrastructure – network bandwidth, the number of data processing centers (Ivanov, 2020; Petrov, 2021). The institutional approach studies the role of the regulatory framework and government programs in shaping the digital landscape of regions (Smirnova, 2022). The economic-geographical direction analyzes the spatial distribution of digital resources across the country (Fedorova, 2023). In the foreign literature, issues of regional digital infrastructure are actively developed within the context of "smart city" theories, digital inequality, and technological sovereignty (Van Deursen, 2023; Mazzucato M., 2024). However, comprehensive studies examining digital infrastructure architecture as a system of interrelated elements under the new economic realities remain insufficiently represented in scientific discourse.

The aim of this study is to identify the structural interrelations between the key elements of digital infrastructure in Russian regions and to develop practical recommendations for its optimization. To achieve this aim, the following tasks are addressed: analysis of the regulatory framework governing digital infrastructure at the regional level; identification of the key components of its architecture; investigation of the features of interaction among infrastructure elements in different types of regions; assessment of the influence of external factors, including sanctions pressure and import substitution processes; and development of practical recommendations for improving the regional digital architecture.

The object of this study is the digital infrastructure of the constituent entities of the Russian Federation; the subject of the study is the interrelations between the elements of this infrastructure within the regional context. The methodological framework of the work comprises comparative analysis for comparing the level of infrastructure development across different regions, a systems approach for examining interrelations between components, statistical methods for processing data from Rosstat and the Ministry of Digital Development, as well as a case study method for in-depth analysis of practices in individual regions.

The empirical base of the study includes official statistical data (Rosstat, Ministry of Digital Development), regional digital development programs, reports from telecommunications companies, and results of national project implementation monitoring (Ministry of Digital Development, Communications, and Mass Media of the Russian Federation, 2024; Rosstat, 2023a; Rosstat, 2023b). The scientific novelty of the work lies in a comprehensive analysis of digital infrastructure architecture taking into account new economic conditions, the development of a typology of regions based on the nature of interrelations between infrastructure elements, and

the identification of the specific impact of sanctions on its various components.

Theoretical foundations of the study

Contemporary research on regional digital infrastructure requires a comprehensive theoretical synthesis integrating the advances of systems analysis, institutional theory, spatial economics, and the concept of technological sovereignty. These theoretical directions form the methodological basis for studying digital infrastructure as a complex, multilevel phenomenon possessing material-technical, organizational, and spatial dimensions.

Within the framework of the systems approach, originating from L. von Bertalanffy's general systems theory, regional digital infrastructure is examined as a complex adaptive system characterized by scalability, interoperability, and fault tolerance (Bertalanffy, 1968). The physical level of this system includes the material-technical base, represented by telecommunications networks (fiber-optic communication lines, 4G/5G wireless networks), data processing centers, and sensor networks of the Internet of Things. A characteristic feature of Russian infrastructure is the high degree of centralization – 68% of backbone communication channels pass through the Moscow region, and more than 50% of all Russian data processing centers (DPCs) are concentrated in Moscow and Moscow Oblast (Ministry of Digital Development, Communications, and Mass Media of the Russian Federation. 2024). Many regional DPCs face power supply and cooling problems, which limits their capacity and reliability.

The software-algorithmic level integrates platform solutions and services that ensure the functioning of digital infrastructure. Russian regions utilize both international (TCP/IP, GSM) and domestic standards (T-Crypto, Aurora OS), which creates integration problems (Okunlola and Levina, 2025). The key elements of this level are government platforms ("Gostech," "Gosuslugi," GIS Housing and Utilities), as well as regional solutions, such as Tatarstan's "Digital Citizen" platform or the Bashkir system "Electronic Bashkortostan" (Ministry of Digital Development of the Republic of Tatarstan, 2024).

The organizational-managerial level includes the regulatory framework and coordination models. Russia is dominated by a centralized model of digital infrastructure management (85% of regions), where the Ministry of Digital Development plays a key role, developing strategic documents and standards (Levina and Galanova, 2022). The regulatory framework includes Federal Laws No. 149-FZ and No. 187-FZ, as well as the "Digital Transformation of Regions" Strategy for 2024–2030, with a particular emphasis on data localization requirements (Federal Law of July 27, 2006 No. 149-FZ; Federal Law of July 26, 2017 No. 187-FZ).

Spatial Aspects of Digital Development

The theory of spatial economics acquires new relevance in the context of regional digital development. Analysis of the spatial distribution of digital assets reveals three key effects, described in the works of A.G. Granberg and M. Porter (Granberg, 2018; Porter, 2020):

1. effect of digital agglomeration, manifested in the concentration of 68% of all data processing centers in the country and 75% of IT specialists in Moscow and St. Petersburg. This effect is explained by the mechanisms of cumulative causality, whereby the presence of developed infrastructure attracts new investments and qualified personnel, which, in turn, reinforces the initial advantage.

2. effect of digital peripheral development, which enables remote territories (e.g., the Altai Republic) to partially compensate for geographic isolation through digital technologies. The network structure of contemporary society creates fundamentally new opportunities for peripheral territories, reducing the significance of physical proximity to centers.

3. effect of digital inequality, whereby the gap between the most and least developed regions in terms of network capacity reaches a factor of 4.7. Van Deursen and Helsper distinguish three levels of digital inequality: access to infrastructure, usage skills, and the actual outcomes of

applying digital technologies (Van Deursen and Helsper, 2023).

Institutional Aspects of Digitalization

The institutional approach, developed in the works of D. North, A.E. Shastitko, and G.B. Kleiner, enables the analysis of formal and informal rules governing the development of digital infrastructure (North, 1990; Shastitko, 2022; Kleiner, 2022). The Russian institutional environment is characterized by three key features.

1. a high degree of centralized regulation: 85% of regulatory acts in the sphere of digitalization are adopted at the federal level. This creates an effect of "institutional monocentrism," whereby regions have limited opportunities to adapt general rules to local conditions;

2. the dominance of vertical over horizontal linkages. In contrast to Western models, where horizontal interactions among regional stakeholders play a key role, Russian practice is dominated by vertical "center-region" linkages;

3. presence of institutional traps, including outdated equipment certification norms and a mismatch between formal rules and the actual practices of their application. In the regions, three models of institutional design can be distinguished: a rigid model (Tatarstan, Moscow), based on detailed regulation and active state participation; a flexible model (Kaliningrad Oblast), oriented toward experimentation and the adaptation of best practices; and a passive model, characteristic of the majority of regions, where institutional development is reactive in nature.

Technological Sovereignty

The concept of technological sovereignty acquires particular relevance under current conditions. In the works of M. Mazzucato, R.H. Weber, and B.N. Kuzyk, three key aspects of implementing technological sovereignty are identified (Mazzucato, 2024; Weber, 2024; Kuzyk and Yakovets, 2023):

1. import substitution of critical technologies. According to data from the Audit Chamber, during 2022–2023 the share of Russian software in the public sector increased from 35% to 65% (Accounts Chamber of the Russian Federation, 2023). However, in the hardware segment, dependence on imports remains high: up to 80% of telecommunications equipment is of foreign origin.

2. formation of closed technological cycles. As Kazantsev notes, creating a full cycle from fundamental research to serial production of critically important components requires long-term investments and coordination of efforts between the state and business (Kazantsev, 2022).

3. development of competencies. Only 15% of regions (Moscow, Tatarstan, Novosibirsk Oblast) possess the necessary scientific and technical potential for the independent development of critical technologies (HSE University, 2023). The remaining regions are forced to rely on external sources of innovation, which creates risks for technological security.

Integrative Model

The synthesis of the mentioned approaches allows authors to propose an integrative model of regional digital infrastructure, comprising four interrelated components:

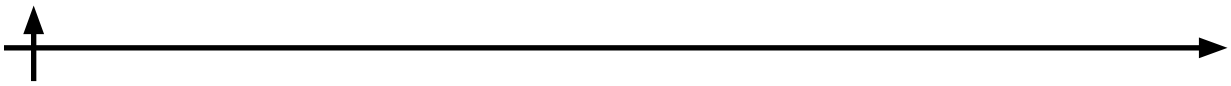
— Structural component – physical (telecommunications networks, DPCs), software (platforms, services), and organizational elements (governance institutions);

— Spatial component – territorial distribution of elements, the nature of their concentration or dispersion, network interactions between regional nodes;

— Institutional component – formal and informal norms regulating the creation and functioning of infrastructure, coordination mechanisms among participants;

— Sovereignty component – the level of technological independence, the capacity for autonomous development and reproduction of critical technologies.

The effectiveness of digital infrastructure architecture is determined by the balance between standardization, which ensures compatibility of elements, and flexibility, which allows



adaptation to the specific conditions of a given region. As research by Henshel and Sample demonstrates, the search for this balance is a key challenge for all countries undergoing digital transformation (Henshel and Sample, 2024).

Research Methodology

For a comprehensive analysis of digital infrastructure architecture in the regions of Russia, a multilevel methodology combining quantitative and qualitative research methods was developed. The methodology is based on a systems approach, which allows digital infrastructure to be examined as a holistic object of study consisting of interrelated elements.

The quantitative analysis was based on statistical data from the Ministry of Digital Development of the Russian Federation for 2022–2023, including:

— Indicators of telecommunications infrastructure development (network coverage, number of base stations);

— Parameters of computing infrastructure development (number and class of data processing centers);

— Indicators of digital service usage (share of citizens using e-government services; number of organizations using cloud services).

The qualitative analysis included:

— Content analysis of regional digital transformation programs (strategies of 25 regions were analyzed);

— Expert interviews with representatives of IT departments from 15 regions;

— Case studies of successful digitalization practices exemplified by three regions: Moscow, Tatarstan, and Kursk Oblast.

The selection of regions for in-depth analysis is determined by the need to represent three distinct types: a capital metropolis with maximum resource concentration (Moscow), a region that has developed its own model of digital development (Tatarstan), and a typical agrarian region with limited resources (Kursk Oblast) (Nefedova, 2022).

Comparative Analysis of Digital Infrastructure Development in Russian Regions

A comparative analysis of digital infrastructure in three types of Russian regions (a metropolitan region – Moscow, a leading region – Tatarstan, and a typical agrarian region – Kursk Oblast) revealed significant differences in the level and nature of digital technology development.

Moscow demonstrates the most developed digital infrastructure. 5G network coverage reaches 82% of the city's territory (MTS, 2023). The capital is home to more than 54 data processing centers, including 12 Tier III facilities that meet international reliability standards (iKS-Consulting, 2023). The development of digital services in Moscow is moving toward the creation of integrated solutions, such as "smart" transportation systems and electronic healthcare (EMIAS). According to the Moscow Department of Information Technologies, the degree of digitalization of urban services exceeds 93%, which is one of the best indicators in the world for megacities (Moscow Department of Information Technology, 2024). Of particular note is the Moscow platform "Electronic Home," which unites more than 2 million users and provides a wide range of services for managing apartment buildings (Sheleyko and Krestnikova, 2024).

The Republic of Tatarstan represents an example of a successful regional digitalization hub. 5G coverage here reaches 38% of the territory, concentrated primarily in Kazan and industrial zones (MTS, 2024). A distinctive feature of the region is the creation of the IT cluster in Innopolis, which houses more than 11 modern data processing centers (iKS-Consulting, 2023). Innopolis, built from scratch as a city for IT specialists, includes a special economic zone,

a university, and a technopark, creating a unique ecosystem for the development of digital technologies. Tatarstan is actively developing its own digital solutions. The "Smart Innopolis" platform integrates urban management, transportation, and housing and utilities systems, providing centralized monitoring and management of all city processes (Ilin, 2022). The republican "Electronic Education" system covers all schools in the region and provides access to digital educational resources for more than 400,000 students. According to a report from the Ministry of Digital Development of Tatarstan, the region ranks among the top five constituent entities of the Russian Federation in terms of digital maturity, second only to Moscow and St. Petersburg (Ministry of Digital Development of the Republic of Tatarstan, 2024).

Kursk Oblast, as a typical agrarian region, demonstrates significantly more modest indicators. 5G coverage is limited to 4.7% of the territory – primarily in district centers (MTS, 2023). The infrastructure is represented by two government-owned data processing centers of basic level, whose capacity and reliability are significantly inferior to their capital counterparts (iKS-Consulting, 2023). Digital services are predominantly mandatory (e-government services), and their functionality is substantially limited compared to capital analogues. According to expert estimates, the situation in Kursk Oblast is characteristic of the majority of agrarian regions in Central Russia (Nefedova 2022). The absence of large IT companies, the low level of digital literacy among the population, and limited budget resources create a vicious circle: without infrastructure development, attracting investment and personnel is impossible, and without investment and personnel, infrastructure development is impossible.

Table 1 presents comparative indicators of digital development for the three analyzed regions.

Table 1. Comparative Analysis of Regional Digital Infrastructure.

Indicator	Moscow	Tatarstan	Kursk region
5G coverage, % of territory	82	38	4,7
Number of data centers	54	11	2
Data centers Tier III	12	0	0
Percentage of digital government services, %	93	78	41
Number of IT specialists per 1000 inhabitants	42	18	3,2
Own digital platforms	«Electronic house», EMIAS	«Smart Innopolis», «E-education»	No

Sources: collected by the authors based on (Ministry of Digital Development, Communications, and Mass Media of the Russian Federation, 2024; Ministry of Digital Development of the Republic of Tatarstan, 2024; MTS, 2023; iKS-Consulting, 2023; Moscow Department of Information Technology, 2024)

Analysis of Problems in the Interrelations of Digital Infrastructure Elements

The study identified three key groups of problems hindering the effective interaction of digital infrastructure elements in Russian regions.

Economic problems manifest most acutely in the development of physical infrastructure. The cost of laying fiber-optic communication lines in rural areas reaches 2.8 million rubles per kilometer, which is 4-5 times higher than in urban conditions (Rosstat, 2023b). This creates significant barriers to ensuring equal access to digital services across the entire territory of the regions. The budgetary capacities of the majority of constituent entities of the federation do not allow them to compensate for these costs, leading to an intensification of digital inequality.

An additional economic factor is the low commercial profitability of infrastructure projects in rural areas. Given low population density and limited solvency of demand, the payback pe-

riod for investments in telecommunications infrastructure can reach 15-20 years, making such projects unattractive to private investors without state support.

Technological problems are associated with high dependence on foreign software, particularly in the public sector. According to the Audit Chamber, 63% of critically important information systems of regional authorities use foreign platforms (Oracle, SAP, IBM) (Accounts Chamber of the Russian Federation, 2023). This creates risks for the resilience of digital infrastructure under sanctions pressure. Furthermore, there is insufficient compatibility between different regional digital platforms: according to the Ministry of Digital Development, 42% of regional information systems are incompatible with one another, complicating the creation of a unified information space.

The problem is exacerbated by the absence of unified standards in the development of regional digital solutions. Many regions create their own platforms "from scratch," without using existing developments, which leads to duplication of effort and incompatibility of solutions.

Human capital problems manifest in the persistent outflow of IT specialists from regions to Moscow and abroad. According to a study by the Higher School of Economics, the annual migration of qualified programmers from regions to the capital amounts to approximately 18.7% of the total number of specialists (Kazantsev, 2022). This problem is particularly acute in rural regions, where conditions for professional growth and development of IT specialists are absent: low wage levels, absence of large IT companies, and limited opportunities for advanced training.

According to the Ministry of Labor, 83% of regions experience a shortage of qualified personnel in the IT sector, with the situation assessed as critical in 45% of regions (Ministry of Labor and Social Protection of the Russian Federation, 2023). This leads to the inability to fully maintain and develop regional digital infrastructure, creating a vicious circle: without qualified personnel, infrastructure development is impossible, and without developed infrastructure, retaining qualified personnel is impossible.

Impact of Sanctions Pressure on Digital Infrastructure Development

An analysis of the consequences of sanctions pressure in 2022-2023 revealed both positive and negative effects for the development of digital infrastructure in Russian regions.

Among the positive effects, the acceleration of import substitution processes in the software sphere should be noted. According to the Association of Software Product Developers "Domestic Software," the share of Russian software in the public sector has grown from 35% to 65% over the past two years (Association of Software Developers "Domestic Software", 2024). Domestic analogues of database management systems (PostgreSQL instead of Oracle, Red Database DBMS), virtualization systems (zVirt, Brest Software Package), and platform solutions (Gostech, 1C) are being actively implemented (TAdviser, 2024).

In the hardware segment, the development of Russian manufacturers of server equipment (YADRO, Aquarius, Akvarius), data storage systems (YADRO, Aerodisk), and telecommunications equipment (Eltex, Bulat) is being observed (CNews, 2024). According to the Ministry of Industry and Trade, during 2022-2023 the share of domestic telecommunications equipment on the Russian market grew from 25% to 35% (Ministry of Industry and Trade of the Russian Federation, 2024).

However, sanctions have also caused serious negative consequences. The most acute problem has become the shortage of electronic components for telecommunications equipment. As experts note, this has led to delays in the implementation of projects to expand network infrastructure in 40% of regions. Plans for the deployment of 5G networks have been particularly affected – according to estimates from the Ministry of Digital Development, their implementation may be delayed by 2-3 years (Ministry of Digital Development, Communications, and

Mass Media of the Russian Federation, 2023).

Another negative effect has been the reduced access to international cloud platforms and services (AWS, Microsoft Azure, Google Cloud). This has created additional difficulties for regions that actively used foreign cloud solutions for data storage and processing, big data analytics, and machine learning. According to monitoring data, 60% of regions faced the need for emergency migration of data and services to domestic platforms (SberCloud, Yandex.Cloud, Cloud.ru), which required additional resource and time expenditures.

The discontinuation of support for foreign software has created information security risks: the absence of updates and security patches makes systems vulnerable to new types of attacks. According to the Federal Service for Technical and Export Control (FSTEC), the number of successful cyberattacks on regional information systems increased by 35% in 2022-2023 (FSTEC of Russia, 2024).

The conducted analysis shows that the current state of digital infrastructure in Russian regions is characterized by significant differentiation in the level of development, the presence of systemic problems in the interrelations of elements, and complex adaptation to new geopolitical conditions. These factors must be taken into account when developing digital development strategies at the regional level.

Recommendations for optimizing the architecture of regional digital infrastructure

Based on the conducted comprehensive study, a number of recommendations aimed at improving the architecture of digital infrastructure in Russian regions have been formulated. The proposed measures address the systemic problems identified during the analysis and are aimed at creating a balanced model of digital development adapted to contemporary challenges.

Recommendations for the Federal Center

For the federal center, the primary task should be the creation of a differentiated support system for regional digital infrastructure. Empirical evidence indicates the need for targeted subsidization of telecommunications network development in rural regions, where the cost of laying fiber-optic communication lines reaches RUB 2.8 million/km (Rosstat, 2023b). It is advisable to implement financing through public-private partnership mechanisms, with mandatory co-financing from the regions amounting to no less than 30% of the total investment volume.

Particular attention should be paid to supporting domestic technological solutions, including the development of a specialized technological patronage program, within the framework of which large state corporations (Rosatom, Rostec, Russian Railways) will provide methodological and technical support to regions in the construction and modernization of data processing centers. Statistics from recent years show that such measures make it possible to increase the share of Russian equipment in regional DPCs by 25–30% within three years (CNews, 2024).

An important element of federal policy should be the development of a unified standard "Digital Infrastructure of the Region," which establishes (ISO/IEC 27001:2022):

— Basic requirements for platform compatibility (API, data formats);

— Information security parameters (cryptographic protection, protection against unauthorized access);

— Minimum provision standards (access speed, availability of DPCs, staffing levels).

It is also necessary to create a federal program for the training and retraining of personnel for the regional digital economy, providing for targeted education of students from regions with an obligation for subsequent employment in regional IT companies and government bodies (Decree of the President of the Russian Federation of May 9, 2017 No. 203).

Recommendations for Regional Authorities

Regional authorities are advised to focus on developing human capital potential and im-

proving digital infrastructure management. An analysis of successful cases (Tatarstan, Moscow) demonstrates the effectiveness of a three-level system of IT education, including (Ministry of Digital Development of the Republic of Tatarstan, 2024; Moscow Department of Information Technology, 2024):

— Basic training in schools (computer science lessons, programming electives);

— Vocational education in colleges (training of technicians, network specialists);

— Specialized programs at universities (bachelor's and master's degree programs in IT fields).

Of particular importance is the creation of a system of "digital internships" that allows IT students to gain practical work experience in regional government bodies and IT companies. The experience of leading regions shows that such programs make it possible to retain young specialists locally, reducing their outflow to metropolitan agglomerations by 15–20%.

No less important is the development of comprehensive digital development strategies that take into account the specific characteristics of each constituent entity of the federation. Such strategies should include:

— Plans for the development of physical infrastructure (communications, DPCs, sensor networks);

— Programs for the digitalization of state and municipal services;

— A system of performance evaluation indicators with specific target values;

— Mechanisms for monitoring and adjustment.

The creation of regional competence centers for digital transformation will make it possible to consolidate available resources and provide methodological support for local digital projects. The functions of such centers should include:

— Accumulation of best practices in digitalization;

— Consulting support for municipalities;

— Coordination of interaction with federal structures;

— Organization of training and professional development.

Recommendations for the Business Community

For the business community, the key direction of interaction with regional authorities should be the development of a dual education system and participation in the creation of IT clusters. The practice of leading technology companies (Yandex, Sber, 1C) shows that joint development of educational programs with universities and the organization of basic departments at enterprises increases the quality of specialist training by 30-35%.

Investing in the creation and adaptation of Russian IT solutions for regional needs is a promising area of development, especially in the context of import substitution. Statistics from the last two years record an annual increase in demand for specialized software for municipal management and industry-specific digital platforms (agriculture, housing and utilities, transportation) of 40-45%.

Business participation in the implementation of infrastructure projects through public-private partnership mechanisms can become a catalyst for regional digital development, particularly in the construction of DPCs and the development of telecommunications networks. The PPP model allows for:

— Attracting private investment given limited budget funds;

— Ensuring professional management of created facilities;

— Sharing risks between the state and business;

— Ensuring higher quality and efficiency of project implementation.

Ways for Development

A promising direction for the development of regional digital infrastructure is the formation of distributed digital ecosystems that unite the resources of several constituent entities of the

federation. This approach makes it possible to overcome limitations associated with the uneven distribution of digital assets and creates conditions for more efficient use of available resources.

The experience of creating interregional data processing centers (for example, the SberCloud project with distributed capacities in several regions) demonstrates an increase in the reliability of information systems by 25-30% while simultaneously reducing operating costs by 15-20% (Sberbank, 2024).

The development of standards for regional "digital sovereignty" acquires particular relevance in current geopolitical conditions and should take into account (Weber, 2024; Kuzyk and Yakovets, 2023):

— Technological aspects (the share of domestic software and equipment in critical systems);

— Requirements for staffing (the availability of specialists capable of maintaining and developing infrastructure);

— Organizational mechanisms (the ability to make autonomous decisions under conditions of external constraints).

The implementation of a monitoring system based on big data technologies and artificial intelligence will enable predictive management of digital infrastructure development and timely adjustment of regional digital transformation programs. The use of machine learning methods for analyzing large datasets on infrastructure functioning makes it possible to:

— Predict bottlenecks and potential failures;

— Optimize resource allocation;

— Identify the most effective practices for their replication.

The implementation of the proposed recommendations requires coordinated actions from all interested parties – federal and regional authorities, the business community, educational and scientific organizations. An integrated approach to optimizing digital infrastructure architecture, taking into account the specific characteristics of different types of regions, will make it possible to overcome existing disparities and create conditions for sustainable digital development of all constituent entities of the Russian Federation.

Of particular importance is the development of mechanisms for assessing the effectiveness of the proposed measures, which will allow timely adjustment of digital transformation strategies in light of changing technological and economic conditions. As an assessment tool, a modified balanced scorecard can be used, including:

— Financial indicators (investment volume, budgetary efficiency);

— Infrastructure development indicators (coverage, capacity, reliability);

— Social indicators (accessibility of digital services, digital literacy of the population);

— Technological sovereignty indicators (share of domestic solutions).

Conclusion

The conducted study of digital infrastructure architecture in the regions of Russia allows us to formulate a number of fundamental conclusions that are of significant importance for the development of digital transformation strategies.

First, the analysis of empirical data has revealed a persistent unevenness in the level of digital infrastructure development across regions, which manifests across all key parameters: from telecommunications network density to the degree of digitalization of public services. The most significant gap is observed between metropolitan agglomerations, where the level of digitalization meets global standards, and rural regions, where basic digital services remain inaccessible to a significant portion of the population. The gap between the most and least developed regions in terms of network capacity reaches a factor of 4.7.

Second, the main systemic problems hindering the uniform development of digital infra-

structure include chronic underfunding of digital transformation projects in the majority of constituent entities of the federation, an acute shortage of qualified personnel (an annual outflow of 18.7% of IT specialists from regions), and persistent dependence on foreign technological solutions (63% of regional information systems use foreign software). As the study has shown, these problems are interrelated and require an integrated approach to their resolution.

Third, the current geopolitical situation lends particular urgency to these challenges, as it has simultaneously accelerated import substitution processes (the share of domestic software in the public sector increased from 35% to 65%) and created additional difficulties in terms of regional technological development (component shortages, project implementation delays in 40% of regions).

Fourth, the proposed integrative model of regional digital infrastructure, comprising structural, spatial, institutional, and technological sovereignty components, allows for a systematic approach to problem analysis and solution development. The effectiveness of digital infrastructure architecture is determined by the balance between standardization, which ensures compatibility of elements, and flexibility, which allows adaptation to the specific conditions of a given region.

Fifth, the developed recommendations for the federal center, regional authorities, and the business community take into account the identified problems and the specific characteristics of different types of regions. Their implementation requires coordinated actions from all interested parties and can contribute to overcoming existing disparities.

Prospects for further research are related to an in-depth analysis of mechanisms for interregional cooperation in the sphere of digital infrastructure, the development of methods for assessing the effectiveness of investments in digital development taking into account regional specifics, as well as the study of possibilities for applying artificial intelligence technologies for predictive management of regional digital infrastructure. Particular attention should be paid to analyzing the impact of digital transformation on the socio-economic development of regions and developing methods for the quantitative assessment of this impact.

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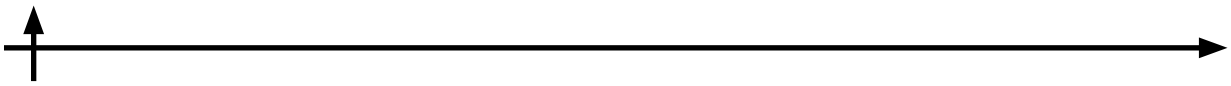

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