

TRANSFORMATION OF THE ROLE OF INFRASTRUCTURE DURING CRISIS PERIODS AS A FACTOR OF ECONOMIC SYSTEM RESILIENCE

Ellada A. Tikhonovich^{1(*)}, Elena G. Russkova¹, Valentin A. Dzedik¹, Irina D. Anikina¹, Anastasia A. Dzhikiya¹

¹ Volgograd State University, Volgograd, Russia

*Corresponding author: tihonovichea@volsu.ru

Abstract. This study examines the transformation of the role of infrastructure during crisis periods from the perspective of a systems approach to the analysis of economic resilience in the context of the global shocks of 2020–2024, with particular attention to the conceptualization of the phenomenon of functional dualism in infrastructure systems manifested in the simultaneous activation of primary and auxiliary target functions under emergency conditions. The study is grounded in an empirical analysis of statistical data from the World Bank, OECD, and International Monetary Fund for the period 2019–2024, covering infrastructure investment dynamics across 142 countries, with total projected investment exceeding USD 106 trillion through 2040. The central hypothesis holds that digital infrastructure has evolved into a meta-infrastructure system capable of sustaining the functioning and reproduction of all other infrastructure types. Crisis infrastructure, defined through the creation of mechanisms to counter external negative impacts, is incorporated within the productive, informational, social, technical-technological, and organizational infrastructure types. During crisis periods, all infrastructure types are mobilized within a constrained spatiotemporal continuum and a specific societal context emerging as a response to the crisis: through the deployment of all NBICS-convergence tools and technologies, reserve financing, and the concentration of human and material resources.

Keywords: crisis infrastructure, functional dualism, digital infrastructure, meta-infrastructure, economic plasticity, NBICS-convergence, resilience of economic systems, COVID-19.

1. INTRODUCTION

The global COVID-19 pandemic constituted an unprecedented stress test for economic systems of various types and levels of development, revealing the critical dependence of national economic resilience on the quality of infrastructure complexes [1]. According to World Bank data, in the first year of the pandemic (2020), global private-sector infrastructure investment contracted by 52%, falling from USD 96.7 billion to USD 45.7 billion; however, a significant recovery to USD 71.2 billion was already observed in 2021. By 2024, investment had surpassed pre-pandemic levels, reaching USD 100.7 billion - marking the first time the USD 100 billion threshold had been crossed and representing a 16% increase compared to 2023 [2].

The theoretical significance of studying the transformation of infrastructure's role under crisis conditions stems from the need to reconceptualize infrastructure as a strategic factor of economic resilience, one capable of shaping the developmental trajectories of economic systems under uncertainty. As noted in OECD research, the pandemic demonstrated the critical role of infrastructure systems both in sustaining economic activity and in enabling effective responses to unforeseen threats [3].

The relevance of this problem is further amplified by the need for large-scale investment in the modernization of infrastructure systems: according to McKinsey & Company estimates (2025), cumulative infrastructure investment requirements through 2040 will amount to approximately USD 106 trillion [4].

2. MATERIALS AND METHODS

Academic research devoted to analyzing the role of infrastructure in ensuring economic resilience during crisis periods is characterized by the relative novelty of its subject domain. Classical works in infrastructure economics, represented by studies by Aschauer and by Calderón and Servén, focused primarily on assessing the contribution of infrastructure investment to long-term economic growth under conditions of normal economic functioning [5].

The specific role of infrastructure during crisis conditions received substantial impetus for development in the context of COVID-19 pandemic analysis. The study by Katz, Jung, and Callorda (2020) provided one of the first systematic pieces of evidence that digitalization can significantly mitigate the economic damage caused by

COVID-19: countries with higher broadband penetration rates were able to offset up to 75% of their economic losses [6]. Subsequent empirical research conducted by Li (2022) on data from 3,142 US counties identified a statistically significant negative correlation between digital divide indicators and cumulative COVID-19 morbidity and mortality rates [7].

The analytical frameworks for infrastructure resilience developed in publications by the OECD, the Global Infrastructure Hub, and the CDRI introduce a multidimensional understanding of infrastructure resilience encompassing physical, operational, financial, and governance resilience [8]. Theoretical concepts relevant to analyzing the transformation of infrastructure's role under crisis conditions include the concept of economic plasticity, which describes the capacity of economic structures to undergo residual deformation while maintaining functional integrity [9].

The methodological framework of the study is based on the integration of systems analysis and network analysis in examining the role of infrastructure in ensuring economic resilience under crisis conditions. The systems analysis approach treats infrastructure as a complex hierarchical system of interrelated subsystems at various levels, while the network approach conceptualizes infrastructure as a set of nodes and links ensuring flows of goods, services, information, and energy.

The empirical basis of the study draws on several types of data that enable a multidimensional analysis of infrastructure dynamics and its impact on economic resilience during the COVID-19 crisis. Panel data on infrastructure investment cover 142 countries for the period 2019–2024, sourced from the World Bank's Private Participation in Infrastructure database. Economic performance indicators are drawn from World Bank, IMF, and national statistical agency databases.

A key element of the methodology is the construction of an Infrastructure Readiness Index, which aggregates indicators of development across different infrastructure types into a single composite indicator. The composite index includes the following sub-indices with corresponding weights: transport infrastructure (25%), energy infrastructure (20%), telecommunications infrastructure (25%), digital infrastructure (20%), and social infrastructure (10%).

Table 1. Structure of the Composite Infrastructure Readiness Index.

Sub-index	Weight (%)	Key Indicators
Transport infrastructure	25	Road quality, railway network density
Energy infrastructure	20	Electricity supply reliability, share of renewables
Telecommunications infrastructure	25	Mobile penetration, internet coverage
Digital infrastructure	20	Data center density, digitalization of public services
Social infrastructure	10	Healthcare accessibility, education

To assess the causal effect of infrastructure on economic resilience, a difference-in-differences methodology is applied, enabling identification of the effect of infrastructure development by comparing the dynamics of economic indicators in countries with high and low infrastructure readiness before and after the onset of the COVID-19 pandemic.

3. RESULTS

The level at which the transformation of infrastructure's role under crisis conditions is examined must be grounded in the recognition that academic work on crisis infrastructure remains fragmented, owing to the insufficient level of scholarly attention to this subject domain.

As a result of the exogenous epidemiological factor's impact on infrastructure functioning and mechanisms, new challenges and constraints emerged. Following the transition from factor-based infrastructure types to crisis structures, analysis and adjustment are required and these must be conducted on the basis of a systems approach to understanding the goals and objectives, priorities and imperatives, as well as the suite of programs and projects developed and implemented by public authorities and economic organizations.

Crisis infrastructure, defined through the creation of mechanisms to counter external negative impacts, is incorporated within the productive, informational, social, technical-technological, and organizational infrastructure types. During crisis periods, all types of infrastructure are mobilized within a constrained spatiotemporal continuum and a specific societal context (emerging as a response to the crisis): through the

deployment of all NBICS-convergence tools and technologies, reserve financing, and the concentration of human and material resources.

The systems approach enables examination of crisis infrastructure as a complex set of relationships and obligations among society, business, and the state in which the state's role as guarantor of security at all levels of governance is dominant. The performance of the regulatory function of crisis infrastructure contributes to ordering the influence of system elements and returning them to the zone of dynamic equilibrium of the pre-crisis system. To achieve this goal, it is necessary to define the composition of elements of the crisis infrastructure system, which must possess the requisite set of functions.

The factor method allows crisis infrastructure to be classified in accordance with the transformational and transactional mechanisms of social production. Under crisis conditions, a substantial burden falls on transactional infrastructure, which serves as the linking element between market agents and the institutional, organizational, and informational infrastructure of the market economy. The economic system modified by the COVID-19 pandemic underwent changes in the domain of infrastructure. The transformation of infrastructure is understood here as a complex and contradictory process of change in its principal types and in its target function a process occurring as a result of qualitative shifts in the structure of the economic system as a whole [10].

Evidence of these transformational changes is provided by the emergence of digital infrastructure as a meta-infrastructure: one that possesses all the characteristics of infrastructure while simultaneously being capable of ensuring the conditions for the functioning and reproduction of infrastructure as a whole, and which performs the role of an auxiliary element in crisis situations.

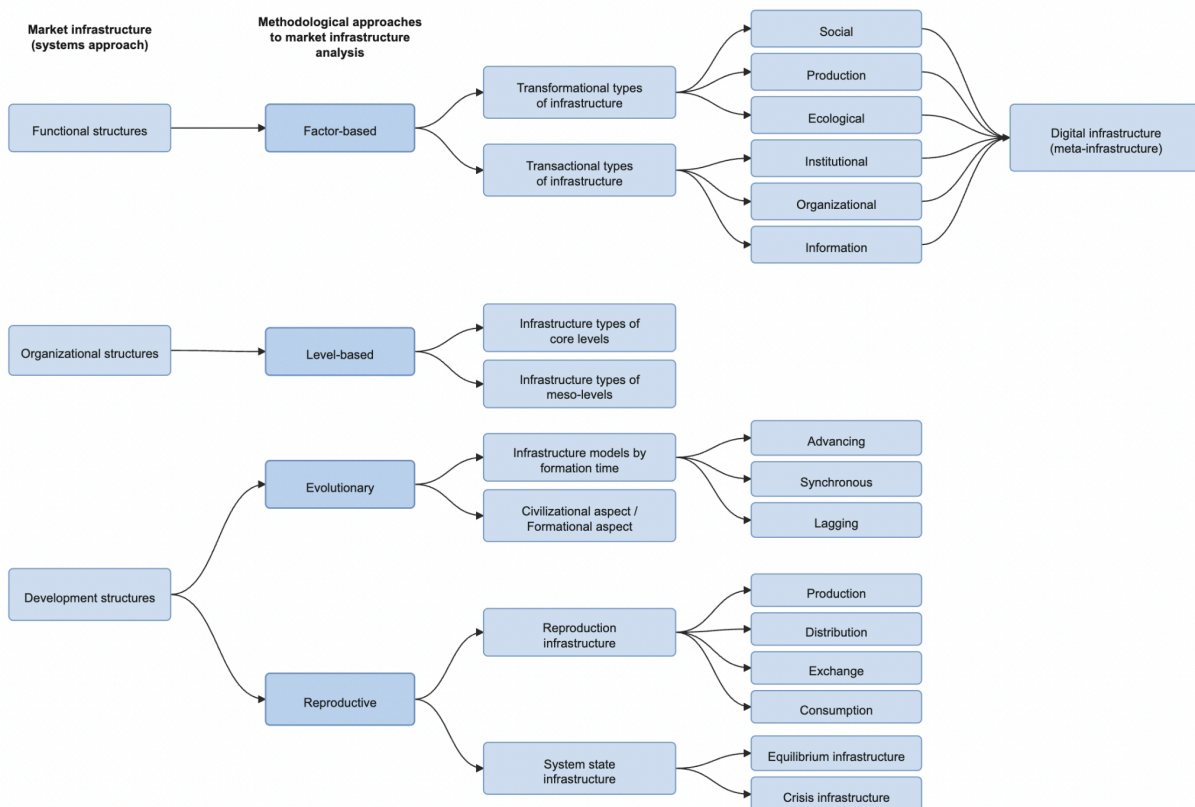


Fig. 1. The place of digital infrastructure within the market infrastructure system.

The results of the empirical analysis of infrastructure's impact on economic resilience during the COVID-19 pandemic demonstrate the existence of statistically significant and economically substantial effects of infrastructure readiness on the capacity of national economies to withstand crisis shocks [11]. The baseline difference-in-differences model shows that the coefficient for the interaction between high infrastructure readiness and the pandemic period equals 2.37 percentage points (standard error 0.68, p-value < 0.001) for real GDP growth rates [11].

Disaggregation of results by individual infrastructure type reveals that digital infrastructure exerted the strongest impact on economic resilience: a one-standard-deviation increase in the digital infrastructure sub-index was associated with a reduction of 3.2 percentage points in cumulative GDP losses over the 2020–2021 period [11]. This is consistent with data from the International Telecommunication Union, according to which countries with the highest pre-pandemic investment in ultra-broadband network deployment were able to minimize network performance degradation during the peak load period in the spring of 2020 [12].

Table 2. Estimates of the impact of different infrastructure types on economic resilience.

Infrastructure type	Coefficient (p.p.)	Std. error	t-statistic	p-value
Digital infrastructure	3.42	0.89	3.84	<0.001
Telecommunications infrastructure	2.87	0.76	3.78	<0.001
Energy infrastructure	1.85	0.61	3.03	0.003
Transport infrastructure	1.23	0.54	2.28	0.023

Analysis of the mechanisms through which infrastructure influences economic resilience identifies two principal transmission channels: a direct channel associated with enabling the continuation of economic activity under conditions of physical constraints, and an indirect channel driven by the reduction of transaction costs [13]. Quantitative estimation of the direct channel's contribution indicates that each additional percentage point in the share of workers who transitioned to remote work was associated with a mitigation of GDP decline of approximately 0.15 percentage points on a quarterly basis [14].

Table 3. Dynamics of economic losses as a function of infrastructure readiness level.

Infrastructure quartile	GDP losses 2020–2021 (%)	Unemployment 2020 (%)	Recovery (quarters)	Growth rate (%)
Q1 (low level)	–12.8	14.2	11	1.16
Q2 (below average)	–9.6	11.7	9	1.07
Q3 (above average)	–6.4	9.3	7	0.91
Q4 (high level)	–3.2	6.8	5	0.64

These data demonstrate that countries with a high level of infrastructure readiness experienced cumulative GDP losses of only 3.2%, compared to 12.8% for countries with a low level, corresponding to an almost fourfold difference in the depth of the economic shock [15].

The concept of functional dualism of infrastructure receives empirical confirmation in the analysis of shifts in infrastructure utilization patterns during the crisis: alongside its primary function of sustaining normal economic processes, infrastructure activated an auxiliary function of maintaining the minimum necessary level of critically important services [16]. Statistical analysis of data on telecommunications network capacity utilization shows that during the peak load period in spring 2020, the traffic structure changed radically: the share of video conferencing increased from 3–5% to 25–30%, the share of online education rose from below 1% to 12–15%, and the share of telemedicine grew from near-zero levels to 3–5%.

Regional differentiation of results shows that the protective effect of infrastructure was especially pronounced in highly urbanized countries: in a sample of 45 countries with an urban population share exceeding 75%, the interaction coefficient reached 3.84 percentage points ($p < 0.001$) [17].

4. DISCUSSION

The empirical results on the impact of infrastructure on economic resilience during the COVID-19 pandemic make a substantial contribution to the theoretical understanding of infrastructure as a strategic factor of economic resilience [17]. The central theoretical result of the study is the conceptualization of the phenomenon of functional dualism of infrastructure manifested in the simultaneous realization of the primary target function (ensuring efficient production and exchange) and the auxiliary target function (maintaining the minimum necessary level of critically important economic and social processes under emergency conditions) [17].

The concept of infrastructure plasticity introduced in this study, describing the capacity of infrastructure systems to undergo residual deformation while maintaining functional integrity, conceptually complements the existing notions of resilience and robustness in the literature [18]. Empirical evidence of infrastructure plasticity is observable in the long-term shifts in infrastructure utilization patterns following the acute phase of the pandemic: the share of workers primarily working from home stabilized at approximately 20–25%, significantly exceeding the pre-pandemic level of 6.5%, yet substantially below the peak value of 35–40% during lockdowns [19].

Of particular significance is the identified heterogeneity of infrastructure effects by type: the dominant role of digital infrastructure (impact coefficient of 3.42 percentage points) compared to traditional infrastructure types confirms the hypothesis of digital infrastructure's transformation into a meta-infrastructure [11]. Digital infrastructure operates not merely as an additional factor of production, but as a higher-order infrastructure that determines the efficiency of all other infrastructure types through the provision of informational transparency and real-time coordination of multiple agents [18].

The concept of NBICS-convergence integrating nano-, bio-, information, cognitive, and social technologies into an integrated ecosystem of innovative development receives empirical confirmation in the analysis of the mechanisms through which digital infrastructure ensured economic resilience during the pandemic [20]. The successful functioning of telemedicine platforms required integration with biomedical technologies, the use of artificial intelligence for diagnostics, and mechanisms for maintaining patient trust.

The practical implications of the study for infrastructure policy include the need to reassess the priorities of infrastructure investment toward greater concentration on the development of digital infrastructure as the foundational layer that ensures the functioning of all other infrastructure systems [21]. Specific recommendations include:

1. Prioritizing investment in the deployment of ultra-broadband networks with sufficient capacity to maintain quality service provision under conditions of significant peak loads, with particular emphasis on ensuring uniform geographic coverage;
2. Incentivizing the development of modular and decentralized infrastructure system architectures, which provide greater resilience to localized disruptions through the capability for autonomous operation of individual modules;
3. Creating mechanisms to ensure redundancy in critical infrastructure elements through the maintenance of reserve capacity capable of absorbing shock-level increases in demand;
4. Developing institutional coordination mechanisms for various infrastructure operators and ensuring the prioritization of access to infrastructure services in crisis situations through the establishment of clear response protocols.

The limitations of the study are associated with several methodological aspects. The difference-in-differences methodology employed presupposes the validity of the parallel trends assumption, the violation of which may

lead to biased estimates of the causal effect [22]. The focus on short- and medium-term infrastructure effects (the observation period is limited to 2019–2024) precludes the identification of potential long-term consequences of structural changes. The heterogeneity of the characteristics of the COVID-19 pandemic as a crisis shock limits the generalizability of the results to other types of crises.

5. CONCLUSION

The study of the transformation of the role of infrastructure during crisis periods as a factor of economic system resilience, based on a comprehensive analysis of empirical data for 142 countries, yields a number of fundamental conclusions. The central finding is the empirical confirmation of the hypothesis that infrastructure plays a critical role in determining the capacity of economic systems to withstand crisis shocks and to achieve rapid recovery of economic activity.

Countries with a high level of infrastructure readiness experienced cumulative GDP losses of only 3.2% during 2020–2021, compared to 12.8% for countries with a low level, corresponding to an almost fourfold difference in the depth of the economic shock [22]. This confirms infrastructure's status as a strategic factor of economic security, comparable in significance to such traditionally recognized determinants of resilience as the fiscal position of the state.

The concept of functional dualism of infrastructure developed in this study, describing the mechanism of simultaneous activation of primary and auxiliary target functions, contributes to the theoretical understanding of infrastructure as an adaptive system. The effectiveness of switching between functional modes is determined by the structural characteristics of infrastructure (degree of modularity, decentralization, and redundancy of critical elements) and by the quality of institutional coordination mechanisms.

The concept of infrastructure plasticity introduced here expands the existing conceptual apparatus for analyzing the resilience of infrastructure systems, offering an alternative perspective that recognizes that under extreme shocks the desirable outcome may not be full restoration of the system's original state, but rather its stabilization in a new equilibrium.

The identified dominance of digital infrastructure in ensuring economic resilience confirms the hypothesis of digital infrastructure's transformation into a meta-infrastructure that ensures the functioning and coordination of all other infrastructure systems. Digital infrastructure operates as a higher-order infrastructure, determining the efficiency of utilization of all other infrastructure types.

Directions for further research include: extending the temporal horizon of analysis to capture long-term effects; conducting comparative analysis of the role of infrastructure in ensuring resilience to different types of crisis shocks; deepening investigation of the mechanisms of interaction among different infrastructure types; and analyzing the institutional determinants of the effectiveness with which infrastructure potential is utilized.

Acknowledgments

The research was carried out with financial support from the Ministry of Education and Science of the Russian Federation under project FZUU-2023-0002 "A New Paradigm for Forming the Economic-Legal Mechanism of Spatial Development of the Russian Federation under Post-Pandemic Conditions, Digital Transformation, and Local and Global Challenges."

REFERENCES

1. Davydov A.A., Mamedyarov Z.A., Khorolskaya M.V. et al. *The world after the pandemic: global challenges and prospects for development* (Global Development, iss. 23, Moscow, IMEMO 2022), DOI: 10.20542/978-5-9535-0599-4 (in Russ.). Available at: <https://publications.hse.ru/pubs/share/direct/579049788.pdf>
2. World Bank, *Private Participation in Infrastructure Annual Report 2024* (World Bank Group, Washington, DC, 2024). Available at: <https://ppi.worldbank.org/en/ppi>
3. OECD, *COVID-19 and a New Resilient Infrastructure Landscape* (OECD Publishing, Paris, 2021). Available at: https://www.oecd.org/en/publications/covid-19-and-a-new-resilient-infrastructure-landscape_d40a19e3-en.html?__cf_chl_rt_tk=RAOxV3RgDjEaPknom9UKJlqYrT8n3DcUtPrEgSpjH98-1766056207-1.0.1.1-v3REEskeTkOy1A2zNQGgRRZONEtErEJ53vf2khj9G88
4. McKinsey & Company, *The Infrastructure Moment: Investing in the Infrastructure of Modern Society* (McKinsey Global Institute, 2025). Available at: <https://www.mckinsey.com/~media/mckinsey/industries/infrastructure/our%20insights/the%20infrastructure%20moment/the-infrastructure-moment-investing-in-the-expanding-foundations-of-modern-society.pdf>
5. C. Calderón and L. Servén, Policy Research Working Paper No. 3400, *The Effects of Infrastructure Development on Growth and Income Distribution* (World Bank, 2004). Available at: <https://documents1.worldbank.org/curated/en/438751468753289185/pdf/WPS3400.pdf>

6. R. L. Katz, J. Jung and F. Callorda, “Can Digitization Mitigate COVID-19 Damages? Evidence from Developing Countries,” *Evidence-Based Policy* 3, 1–18 (2020). DOI:10.2139/ssrn.3600829
7. F. Li, “COVID-19 Outcomes and the Digital Divide in the United States: Disconnected in a Pandemic,” *Health & Place* 78, 102930 (2022). DOI: 10.1016/j.healthplace.2022.102867
8. Global Infrastructure Hub, *Pandemic Preparedness: Pathways to Resilience through Global Health Infrastructure* (GI Hub, Sydney, 2024). Available at: <https://www.gihub.org/articles/pandemic-preparedness-pathways-to-resilience-through-global-health-infrastructure>
9. M. Farjoun, “Beyond Dualism: Stability and Change as a Duality,” *Academy of Management Review* 35 (2), 202–225 (2010). DOI:10.5465/amr.35.2.zok202
10. E.G. Russkova., E.A. Tikhonovich and V.Yu.Moiseeva «Transformation of the role of infrastructure in times of economic crisis» *Strategies for ensuring the economic security of Russian regions. Materials of the III All-Russian (national) Conference* (2023) (in Russ.).
11. Z. Ji, et al., “Does digital transformation promote economic resilience? Urban-level evidence from China,” *Heliyon* 10 (3), e24896 (2024). DOI: 10.1016/j.heliyon.2024.e26461
12. International Telecommunication Union (ITU), *Economic Impact of COVID-19 on Digital Infrastructure* (ITU, Geneva, 2020). Available at: https://www.itu.int/dms_pub/itu-d/opb/pref/D-PREF-EF.COV_ECO_IMPACT-2020-PDF-E.pdf
13. Recon Analytics, *US Broadband Network Performance during COVID-19 and Beyond* (Recon Analytics, Washington, DC, 2021). Available at: <https://reconanalytics.com/wp-content/uploads/2021/11/ReconAnalytics-Networks-in-the-Pandemic.pdf>
14. J. I. Dingel and B. Neiman, “How Many Jobs Can Be Done at Home?,” *Journal of Public Economics* 189, 104235 (2020). <https://doi.org/10.1016/j.jpubeco.2020.104235>
15. International Monetary Fund, *World Economic Outlook* (IMF, Washington, DC, 2024). Available at: <https://www.imf.org/en/publications/weo/issues/2024/10/22/world-economic-outlook-october-2024>
16. OECD, *OECD Economic Outlook* (OECD Publishing, Paris, 2024). Available at: https://www.oecd.org/en/publications/oecd-economic-outlook/volume-2024/issue-1_69a0c310-en.html
17. A. G. Zaballos, E. Iglesias and A. Adamowicz, *The Impact of Digital Infrastructure on the Consequences of COVID-19 and on Mitigation of Future Effects* (Inter-American Development Bank, Washington, DC, 2020). Available at: <https://publications.iadb.org/en/impact-digital-infrastructure-consequences-covid-19-and-mitigation-future-effects>
18. N. Coleman, et al., “Weaving equity into infrastructure resilience research: a decadal review and future directions Check for updates,” *npj Natural Hazards* 1, 22 (2024). DOI:10.1038/s44304-024-00022-x
19. U.S. Bureau of Labor Statistics, “The rise in remote work since the pandemic and its impact on productivity,” *Beyond the Numbers* 13 (20) (2024). Available at: <https://www.bls.gov/opub/btn/volume-13/remote-work-productivity.htm>
20. M. N. Dudin, “The sixth major cycle in the development of the world economy: the era of nbic-convergence in the agro-industrial complex,” *Problems of Market Economy* 3, 74–82 (2019) (in Russ.). Available at: http://www.ipr-ras.ru/old_site/articles/2019-03-74-82-dudin.pdf
21. A. V. Frolov, “NBIC technologies and directions of their development in the USA,” *Innovations* 9, 35–42 (2013) (in Russ.). Available at: <https://cyberleninka.ru/article/n/nbic-tehnologii-i-napravleniya-ih-razvitiya-v-ssha>
22. E. A. Kapustina, A. I. Sadykov and J. Podgorski, “The role of infrastructure investments in economic growth and balanced regional development,” *Finance: Theory and Practice* 27 (2), 50–65 (2023). (in Russ.) DOI: 10.26794/2587-5671-2023-27-2-50-63
23. M. A. Peters, et al., “Resilience of front-line facilities during COVID-19: evidence from cross-sectional rapid surveys in eight low- and middle-income countries,” *BMJ Global Health* 8 (5), e011568 (2023). DOI: 10.1093/heapol/czad032
24. American Society of Civil Engineers (ASCE), *Bridging the Gap: Economic Impacts of National Infrastructure Investment, 2024–2043* (ASCE, Reston, VA, 2024). Available at: <https://bridgingthegap.infrastructurereportcard.org/wp-content/uploads/2024/05/2024-Bridging-the-Gap-Economic-Study.pdf>