INTEGRATED ASSESSMENT OF THE EFFICIENCY OF REGIONAL INFRASTRUCTURE BASED ON MULTI-CRITERIA APPROACHES IN THE CONTEXT OF GLOBAL CHALLENGES

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Abstract

The article examines the current problem of assessing the effectiveness of infrastructure in the context of modern global challenges such as social issues, environmental change, urbanization and digitalization. The complexity of the concept of "efficiency" is emphasized, which includes not only economic, but also environmental, social, innovative and adaptive aspects. Modern methods of infrastructure assessment are considered, including integrated and multi-criteria approaches that allow taking into account the specifics of various types of infrastructure and identifying bottlenecks in their functioning. The author's method of calculating the integral efficiency index is proposed, which takes into account economic profitability, environmental compliance, social significance, innovative development and adaptability of infrastructure. Using the example of assessing the tourist infrastructure of the region, the practical applicability of the method is demonstrated, and areas for optimization are identified. It is concluded that it is necessary to develop hybrid models combining dynamic adjustments and multi-criteria to ensure the sustainable development of infrastructure in a changing environment.

Keywords: infrastructure efficiency, assessment, sustainable development, economic modeling, multi-criteria analysis, adaptive systems

I. Introduction

In recent years, infrastructure assessment has become a key topic in the context of global challenges: high variability of the external environment, climate crises, urbanization and digitalization. In addition, infrastructure organizations annually implement many projects that significantly affect its structure, performance results, and interaction with the main sectors of the economy. For example, a large number of projects aimed at developing new technologies and materials, creating startups, innovation centers, technology parks, etc. are introduced annually just in the innovative infrastructure of any region of the country. However, the efficiency of such projects of infrastructure organizations varies greatly, and a number of infrastructure sites call their performance indices in question.

It should also be taken into account that the concept of "efficiency" refers to complex economic categories that reveal cause-and-effect relationships between a set of interacting various factors and conditions that determine the state of the economic objects under study.

To assess efficiency, many different approaches and methods are used: complex, factor, mathematical, integral, rating, balance, marginal, using various criteria, indicators and methods of determination. In general, efficiency reflects the relationship between economic results (effects) and the total costs (expenses, investments) that led to their receipt. However, the costs and results are not one-time acts, but complex processes that last a long time and are influenced by many circumstances, not only of a purely economic nature, but also social, organizational, adaptive, scientific and technical, environmental and others. In this regard, there is a need to study the characteristics and level of influence on the efficiency of not only economic indicators (costs and results), but also other non-economic factors. This fact is very relevant for the analysis of the assessment of infrastructure efficiency, the study of the factors determining the success of its functioning, the study of institutional conditions affecting the indices of its activity. However, it is difficult to implement these intentions due to terminological inconsistencies in the scientific literature on the issues of defining the concept of infrastructure efficiency and its content, and determining methods for its assessment.

II. The state of the assessment of infrastructure efficiency in the scientific literature

Theoretical, methodological and applied issues of infrastructure efficiency assessment are reflected in the works of domestic and foreign scientists. They use different approaches and assessment methods depending on the type of infrastructure formation and the objectives of the study.

The assessment of the infrastructure efficiency is carried out on the basis of the application of single-criteria, integrative and multi-criteria approaches and methods.

Single-criterion approaches are aimed at studying a single scientific problem of infrastructure. For example, M. V. Boykova, V. V. Makrusev, V. E. Novikov, T. M. Vorotyntseva [3; 5] studied customs infrastructure, M. Y. Artamonova, T. Y. Kostyuchenko studied logistics infrastructure [16].

Integrative approaches. A number of studies [10] use an integrative approach to assess municipal infrastructure, which includes assessing roads, water supply and sewerage using the analytical hierarchy process and fuzzy-set theory.

The work [9] uses a load-bearing model and a method of analyzing means and variances to assess the bearing capacity of urban infrastructure, which makes it possible to identify imbalances in the development of infrastructure between cities.

Multi-criteria (or multiobjective) methods are distinguished by the fact that several criteria are used to assess the efficiency of spatial infrastructure, such as information support, the process of use and strategic compliance, which is reflected, for example, in the work [15].

Marccus D. Hendricks, M. Meyer, N. Gharaibeh and others proposed a method for the assessment of the infrastructure of areas with public participation to create sustainable infrastructure systems [12].

Nagurney, A., Qiang, Q. studied the efficiency indices of critical infrastructure networks (transport, electrical, Internet networks) [13].

Nieto, M., & Carmona-Benítez, R. proposed an approach to measuring the performance and efficiency indices of future airport infrastructure [14].

Lorenzo-Toja, Y., Vázquez-Rowe, I., Marín-Navarro, D., Crujeiras, R., Moreira, M., & Feijóo, G. developed methods for dynamic assessment of the environmental effectiveness of wastewater treatment plants [11].

In general, foreign scientists believe that infrastructure assessment methods are an obligatory and important aspect of ensuring its sustainability, reliability and efficiency. To analyze and substantiate their findings, they make extensive use of the CIERA methodology – a Critical Infrastructure Elements Resilience Assessment considering the ability of the elements to recover and adapt after destructive events, as well as such methods for assessing the state of infrastructure as the determination of the Infrastructure Value Index (IVI) and the Asset Sustainability Index (ASI),

In this regard, various methods and approaches are used to assess the condition, sustainability and development of various infrastructure systems, including water, transport and digital infrastructures.

The following Russian scientists devoted their works to the study of infrastructure assessment methods: G. F., Balakina, E. B. Kibalov, M. V. Pyatayev [2; 6] (application of the methodology of expert assessment of the project, logical-heuristic models), D. A. Macheret, A. D. Razuvaev [8] (efficiency of transport infrastructure).

In the Russian Federation, alternative approaches are used to assess the efficiency of socially significant infrastructure projects that meet the current stage of economic development of the country. These models are aimed at maximizing the results of capital investments of investors and reducing their payback periods [7]. At the same time, the conditions for the manifestation of a synergistic effect in regional infrastructure facilities are studied [4].

Domestic researchers apply methods for assessing the relative efficiency of infrastructure facilities, use linear programming, modeling, etc. Their works emphasize the role of economic-mathematical and static models that do not take the dynamics of external factors into account and do not pay sufficient attention to the role and influence of social factors on infrastructure systems. Methods based on data analysis and risk accounting are proposed, but their algorithms are poorly adapted to rapidly changing environmental conditions.

In general, modern methods of infrastructure efficiency assessment include the integration of various criteria and the use of multi-criteria approaches, which allows which allows considering the specific characteristics of each type of infrastructure. These methods help to identify bottlenecks and optimize resource use, ensuring sustainable infrastructure development.

The analysis of publications shows a growing interest in multidisciplinary approaches, which allows to reveal the problems in existing approaches. Multi-criteria assessment allows taking into account social aspects of infrastructure sustainability, such as mobility, accessibility and safety, but other aspects of infrastructure, such as ecology, social needs, etc., require further study.

In our opinion, a critical gap in the existing infrastructure research is the static nature of the models, insufficient consideration of social and environmental factors, a certain disunity in the calculations of the indices used, and the lack of an adaptation mechanism.

In this regard, there is currently a lack of comprehensive models for assessment of the efficiency of infrastructures that combine the economy, ecology and society in dynamics with adaptation mechanisms. For example, many calculations of the efficiency of infrastructure facilities often exclude environmental costs, which overestimates the efficiency by 10-15% (data from our study). Ignoring the social aspects of infrastructures can also call into question its efficiency. The above confirms the need to develop a hybrid approach that combines dynamic adjustments and multicriteriality. It is necessary to ensure a synthesis of methods that allow assessing infrastructure as a complex system with feedback.

The relevance of the study is caused by the need for tools capable of assessing infrastructure in the context of climate risks, social transformation and other factors, which are absent in modern works.

III. Methods

Human The research used a system approach, which allowed for an analysis of infrastructure as the interaction of various subsystems (transport, energy, ICT, etc.); an economic modeling, i.e. forecasting costs and benefits over a period of several years, was also used.

The following research methods have been used:

The DEA (Data Envelopment Analysis) method allows evaluating the relative efficiency of objects using linear programming to compare input (costs) and output (results) parameters.

The MCDA (Multiple-Criteria Decision Analysis) method is the proposal and systematization of alternative solutions using qualitative and quantitative criteria in the presence of high uncertainty of the situation and the development of conflict between different social groups. The main aim of this method is to achieve agreement and resolve contradictions among all interested parties directly involved in the decision-making process. By promoting open discussion, MCDA allows for diverse interests and opinions to be considered, which in turn helps to find optimal solutions that take into account the needs of all participants involved. This method provides a structured approach that is particularly relevant in complex situations where alternatives must be evaluated considering multiple factors and possible outcomes. Multi-criteria analysis serves as an important tool for effective communication and high-quality decision-making in management systems.

The LCA (Life Cycle Assessment) method is a method for assessing the ecological footprint.

The Life Cycle Assessment method is carried out according to the ISO standard 14040:2006.

IV. Results

Infrastructure efficiency will be further understood as its ability to provide services with the necessary results, minimal costs and under risks (negative external impact).

Infrastructure adaptability means the ability of a system to maintain functionality under external shocks.

When assessing the infrastructure efficiency, the following principles must be observed.

1. Complexity and integration, meaning the simultaneous consideration of economic, environmental and social factors.

2. Dynamism, i.e. regular updating of basic data characterizing the state of the infrastructure facility.

3. Scalability means the applicability of the efficiency calculation method to infrastructure facilities of different levels and scales.

To determine the infrastructure efficiency, it is proposed to define the integral efficiency index (EI), which takes the economy, ecology, social, innovative factor and adaptability into account. (If necessary, these components can be replaced by others considering the purposes of the efficiency index calculation).

Efficiency index is a type of key performance indicator (KPI) that compares specific indicators with each other.

$$EI = \frac{(C_1 * EP + C_2 * EC + C_3 * SS + C_4 * IN) * AI}{RE},$$

where C_1, C_2, C_3, C_4 denote reduction coefficients. They can have different values (in the range from 0 to 1) in relation to different indicators and in different areas. The sum of the reduction coefficients when calculating the EI must be in the range 0–1. For example, $C_1 = 0.3$; $C_2 = 0.2$; $C_3 = 0.3$; $C_4 = 0.2$;

- EP – economic profitability. It is defined as the ratio of net income to total costs, normalized to 0–1;
- EC – environmental compliance. Defined as an index in the range from 0 to1, where 1 is compliance with ISO standards 14001;
- SS – social significance of infrastructure. It is defined as the result of surveys of target groups on a 5-point scale, normalized to 0–1, where 0 is the minimum significance and 1 is the maximum significance;
- IN - innovative development. It is defined as the ratio of the result from innovations to their costs, normalized to 0–1;
- RE – reduced expenditures presented in millions of monetary units (for example, rubles). They represent all expenses for the life cycle of an infrastructure facility (construction, operation, end-of-life), discounted to the current value;
- AI – adaptability index. It is determined on a scale from 0 to 10, where 0 is the minimum adaptability and 10 is the maximum.

The assessments and criteria for calculating the adaptability index (AI) of infrastructure (or its individual object) include the following parameters (Table 1).

Table 1: *Assessments and criteria for calculating the adaptability index (AI) of infrastructure or its individual object*

Assessment (score)	Infrastructure criterion	Description
0-2	Low adaptability	The object is not able to adapt to changes (e.g. climate, technology)
3-4	Limited adaptability	The object can be adapted only with significant additional costs or changes
5-6	Average adaptability	The object has basic adaptation mechanisms, but requires further development for full stability
7-8	High adaptability	The object is able to adapt to most changes with minimal costs
9-10	Maximum adaptability	The object is fully adaptable, including provisions for unexpected changes

The procedure for compiling the scale is as follows.

1. The key parameters of infrastructure adaptability are determined (for example):

- resistance to climate change (e.g. temperature increase, precipitation level);
- flexibility to technological changes (e.g. introducing new technologies);
- resource security (availability of reserves for modernization);
- legal and regulatory flexibility (ability to comply with changing regulations).

2. Determination of the assessment for each parameter. Experts assess each parameter on a scale from 0 to10.

The final AI value is calculated as the arithmetic mean of all assessments. Calculation example:

- climate stability – 8;
- technological flexibility – 7;
- resource security – 6;
- legal flexibility – 9.

The total value of AI = (8 + 7 + 6 + 9) / 4 = 7.5.

When the situation in the external environment of the infrastructure changes, as well as in its performance indicators, the adaptability index should be re-evaluated.

After the calculation of the efficiency index (EI) it should be interpreted on a scale from 0 to 1, where 0 is the minimum efficiency and 1 is the maximum (Table 2).

Table 2: *Interpretation of the infrastructure efficiency index (EI)*

EI range	Interpretation
0-0.2	Low efficiency. The infrastructure is inefficient and requires significant improvements
0.2-0.4	Satisfactory efficiency. The infrastructure works, but there are reserves for improvement
0.4-0.6	Average efficiency. The infrastructure is efficient but requires optimization
0.6-0.8	High efficiency. The infrastructure works well, the risks are minimal
0.8-1.0	Maximum efficiency. The infrastructure is optimal by all criteria

Here is an example of calculating the efficiency index for a tourist infrastructure facility in one of the regions of Russia based on the results of 2024.

Initial data:

Reduction coefficients: $C_1 = 0.4$; $C_2 = 0.2$; $C_3 = 0.3$; $C_4 = 0.1$

Economic profitability (EP) = 0.8.

Environmental compliance (EC) = 0.6.

Social significance of infrastructure (SS) = 0.9.

Innovative development (IN) = 0.4.

Reduced expenditures (RE) = 11 million rubles.

Adaptability index (AI) = 7.

Let's calculate the weighted sum of the criteria: (0.4*0.8+0.2*0.6+0.3*0.9+0.1*0.4) = 0.75.

Multiply the result by the adaptability index AI: 0.75*7 = 5.25.

Divide the result by the present reduced expenditures (RE): EI = 5.25/11 = 0.48.

Thus, the final value of EI = 0.48. This value can be interpreted as the relative efficiency of the object taking all criteria into account. For comparison with other objects or scenarios, EI can be calculated for each of them and the optimal option can be selected.

Interpretation of the result.

EI = 0.48 indicates average efficiency. The infrastructure facility is efficient but requires optimization.

The indicator can be improved by:

- increasing economic profitability (EP);
- increasing environmental compliance (EC);
- increasing adaptability (AI);
- reducing expenditures (RE).

The given example demonstrates the flexibility of the formula and its applicability for the comprehensive assessment of infrastructure projects.

V. Discussions

The integration of multidisciplinary approaches to the assessment of the infrastructure efficiency allows us to consider not only economic, but also its environmental, social and other aspects. This is especially relevant in the context of global challenges such as climate change, urbanization and digitalization, which require infrastructure systems to be highly adaptable and resilient. The development of hybrid models that combine dynamic adjustments and multi-criteria may become a key direction for further research in this area.

Assessment of the infrastructure efficiency of should be a continuous process, taking both current and future challenges into account. Only a comprehensive approach that combines economic, environmental and social aspects will ensure sustainable development of infrastructure and its ability to adapt to changing environmental conditions.

The use of an integral efficiency index contributes to a more accurate and multi-criteria accounting of factors influencing the infrastructure efficiency, which will have a positive impact on the development of appropriate management decisions.

VI. Conclusions

The study confirmed that the assessment of infrastructure efficiency is a complex and multifaceted task that requires consideration of multiple factors, including economic, environmental, social, innovative and adaptive aspects.

Existing methods of the efficiency assessment are often static and do not sufficiently consider the dynamics of the external environment, which limits their applicability in the context of rapidly changing climatic, technological and social conditions.

Modern approaches to infrastructure assessment, such as integrated and multi-criteria methods, make it possible to take into account the specifics of various types of infrastructure and identify bottlenecks in their functioning.

The integral efficiency index (EI) proposed in the study is a flexible tool that allows for a comprehensive assessment of infrastructure, considering not only economic indicators, but also environmental, social and adaptive parameters. This approach demonstrates its practical applicability using the example of tourism infrastructure assessment, where it was possible to identify the average level of efficiency and determine areas for optimization.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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