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Conceptual model for managing the phases of implementation of infrastructure projects and programmes in the post-war period

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Abstract. The outbreak of Russia's full-scale invasion of Ukraine has caused significant human, economic, and political damage, as well as destruction to infrastructure. However, in the future, all losses incurred should be recovered. Therefore, creating models to manage infrastructure projects is still important, especially in the post-war environment of Ukraine. The purpose of this study was to build a model that would allow for the highest management efficiency in the implementation of infrastructure projects in the post-war period and to describe the possibilities of its practical application. The main methods used in the study were analysis, modelling, and abstraction. Thus, the study built a conceptual model of management of infrastructure projects and programmes in the post-war period. The study also analysed the current theoretical framework for infrastructure project management and highlighted the issue of substantiating the parameters of infrastructure programme and project products. Network models, their features and possibilities of use were described to provide a clearer picture of the project's work and more efficient resource management. The paper emphasised that infrastructure

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projects are often divided into two phases: construction and operation. The study also described the importance of infrastructure projects for the efficient transport of goods and passengers and their impact on the competitiveness of the transport system. This study offers a more profound insight into the specific features of managing the implementation phases of infrastructure projects, especially in the post-war period, and brings new knowledge for management in the context of building large-scale investment programmes

Keywords: economic and mathematical models; water transport; economy of Ukraine; management; macroeconomics

Introduction

Modern water transport infrastructure faces various risks that affect its operation and condition. As of 2023, the water transport infrastructure is exposed not only to military risks of destruction and damage, but also to ageing and natural wear and tear. Therefore, maritime infrastructure should be developed through a sequence of projects and/or development programmes aimed at achieving a certain level of infrastructure performance at each stage. Thus, infrastructure development should be based on the required level of its condition, proceeding from the interests of the state at different levels and in different aspects. Infrastructure projects in the field of water transport correspond to the composition of infrastructure (infrastructure facilities) and may be related to a) modernisation of facilities; b) replacement of facilities; c) restoration of facilities; d) development of existing facilities; e) creation of new facilities. “Modernisation” is associated with the “upgrading” of infrastructure facilities. Specifically, this may relate to handling, navigation, and hydrographic equipment, and alarm systems. “Replacement” of facilities involves the replacement of equipment and systems that have failed (or been damaged as a result of natural disasters, accidents, etc.) with analogous parameters (characteristics). “Restoration” may include repairing equipment, improving waterways, canals, dams, etc. For instance, natural siltation requires cleaning the paths. “The development of existing facilities” is aimed at changing the characteristics of infrastructure. Thus, deepening the bottom near berths, in canals, etc. will allow ports to accommodate larger vessels. Therefore, the restoration of water transport after the war plays a significant role in the further development of Ukraine. It is one of the main components for the movement of goods and passengers in the country, which is why ensuring its reliability is still important to ensure quality and safety, as well as reducing the cost and time of transport. This is another part of the relevance of this study.

Notably, current scientific economic literature lacks sufficient studies that would be capable of describing the potential for Ukraine’s future recovery in times of war or post-war. Nevertheless, there are still some studies on this topic. Thus, recent studies by H. Tanaka (2020) and R. Wagner (2023) “Creation of new facilities” is the widest list of projects from the creation of new information, navigation, hydrographic systems to the construction of a new port or canal. Thus, according to M.A. Vereshchak (2021a), the product of infrastructure projects in the field of water transport is infrastructure facilities that are either created or transformed (restoration, replacement, modernisation, development). Equally significant were the studies that investigated the specific features of Ukraine’s post-war rehabilitation. One of them is the study by L.I. Kuznetsova (2022), in which the researcher described possible trajectories of development of the main types of economic activity in Ukraine in the post-war years.

Thus, the purpose of this study was to ensure the effectiveness of infrastructure projects and programmes in the field of water transport through the development and practical use of programme management models. This will allow for more efficient restoration of Ukrainian infrastructure in the post-war period, leading to both cost and time savings.

Materials and Methods

The study used formulas that describe the features of the model for managing the phases of implementation of infrastructure projects and programmes in the post-war period. Thus, the beta distribution and calculation of the expected duration and variance σ^2 were estimated using the following formulas:

$$\delta^2 = \begin{cases} \gamma \\ \frac{t_{max} - t_{min}}{4} \\ E = x^2 + y^2 \end{cases}. \quad (1)$$

The mathematical expectation was calculated using the following formula:

$$E(_{y_i}) = \overline{Y} = \sum_{i=1}^{n} Yi \frac{\gamma}{n-\alpha}. \quad (2)$$

The economic variance was calculated as follows:

$$\theta^2 = \frac{\sum_{i=1}^{y} [X_{i} \_ X^2]}{i-1}. \quad (3)$$

The confidence interval was calculated as follows:

$$\overline{\gamma} \pm t_{i-1,}{}^{6/2}\sqrt{\frac{\sigma^2}{i-1}}. \quad (4)$$

This study has certain limitations. Specifically, the paper does not provide empirical data based on which the effectiveness of the model could be tested, without which it is difficult to assess the real practicality of its application in certain conditions. The study aims to propose a model, but it is worthwhile to evaluate how it will perform in a particular situation and in comparison with other models in further studies. Moreover, the proposed model is quite complex: it involves the use of petal charts and mathematical equations, which is why its use requires a considerable level of experience for effective implementation. This can reduce the effectiveness of its application in practice, especially in the context of limited resources at the organisational level.

The most important approach used in the study was a systematic one. It allowed combining and analysing all the factors affecting the state of infrastructure in Ukraine within a single system. This also helped predict the future state of losses that the country might suffer due to the war, which helped in building an optimal model for managing the phases of infrastructure projects. Furthermore, a comprehensive project approach was used during the study. It is reflected in the use of various modelling techniques, such as system analysis, graphical modelling, and statistical analysis, used to deal with uncertainty and manage complex economic systems. The synthesis played an essential role in reviewing the data obtained on the potential of constructing infrastructure projects, enabling the drawing of conclusions based on the data. Modelling played a significant role within the framework of the study. Specifically, the modelling method was used to build a petal chart showing the factual indicators of goal achievement and planned values, which allows assessing the level of goal achievement visually. The study also built a mathematical nonlinear model that allows controlling the parameters for infrastructure project products within the selected programmes. Abstraction was also used, which allowed ignoring some of the factors that will affect the ability to restore Ukrainian infrastructure after the war.

Results

1. **Infrastructure project life cycle and PERT method**

Quite often, the creation and development of an infrastructure facility, its operation and management are shaped by different projects. In other words, in the classical life cycle of a new facility project, the operation phase is allocated to a separate project (e.g., the creation and operation of a terminal in a port). Thus, infrastructure projects can be classified as a set of "build-operate" projects. In practice, the investor of a relevant infrastructure project is most often the future operator of the infrastructure facility. Systemic links have been established between infrastructure projects that are part of development programmes and project portfolios at different levels – from a company, a single port, a region, to the country's transport system as a whole (Burkynskyi & Nikishina, 2021).

Network models are considered optimal for describing, planning, analysing and optimising projects and have been demonstrated to be effective in practice. Network modelling often assumes a precisely defined duration of the work that makes up a project. This approach has several advantages:

- this network forms a holistic picture of the set of works; the connections between the elements of the set are clearly covered;
- identification of the critical path allows identifying the work that determines the course of the entire set;
- there is clarity about time reserves to which certain work that is not on a critical path can be postponed, which in turn allows for more efficient management of available resources.

However, the use of deterministic network models is not effective for the purposes set out above due to the large number of random influences, insufficient information, and the inability to predict all aspects of the work. The PERT (Programme (Project) Evaluation and Review Technique) method is essentially an improvement of the critical path method, where the deterministic duration of operations is replaced by the expected duration. To calculate the expected execution time of operations, three estimates of the execution time of an elementary operation t_{min} are used:

- pessimistic estimate of the execution time t_{max} – under the most unfavourable conditions;
- realistic estimate of the time required to complete the test – under normal conditions (Burkynskyi & Nikishina, 2021).

Each phase of the programme lifecycle model has its own system of predictable crisis phenomena that need to be considered in management processes (Dubnitskyi, 2021). Such phenomena in the programme development model form bifurcation points (the concept of bifurcation means a sudden change in quality, a change in the type of system solution), where the development of the system can slow down substantially, or it can be destroyed by internal and external influences. This approach is in line with the conventional description, when the idea of a crisis is reduced to a point – a bifurcation point, where the development of the system is unstable and jumps to a stable alternative branch. The risk of a crisis increases not only because of the launch of large-scale comprehensive measures at a particular stage, but also because of the accumulation of smaller violations and conflicts in the programme. Bifurcation points may reflect accumulated problems related to market vulnerability, supply chain management crises, autonomy crises, supply chain relationship crises, governance and innovation centres crises, trust crises, and competitiveness crises, etc. (Kramskyi *et al*., 2021) The paper notes that in any project (and, consequently, in a programme), two fundamentally different types of stakeholder interaction are implemented: in "milestone situations" and at the stages of the life cycle. Communication and information exchange are perceived as essential activities at each life cycle stage. It is caused by the need to organise joint implementation of pre-planned activities by stakeholders and is aimed at ensuring the information status of stakeholders relevant to their actions in the project. Organisationally directed interaction is implemented at the various stages of the life cycle, as stated by Kulinskyi (2020). The transport infrastructure in Ukraine needs to be improved through the implementation of infrastructure projects, especially after the war. Efficient transport of goods and passengers depends on achieving the best level of transport infrastructure.

Reliable transport infrastructure ensures the quality, safety, cost, and time of transport. This affects the country's transit potential, the competitiveness of the transport system, the efficiency of the transport sector and the competitiveness of domestic goods.

2. **Building a model of economic security of transport infrastructure**

Interaction during phased situations is considered a specific activity of "negotiation" among stakeholders. It occurs due to the necessity of modifying or significantly changing pre-planned activities and is intended to enable the stakeholders to develop a logical alternative for the project's growth that aligns with their values. This type of interaction can only be value-based. The beginning of a "Situation Milestone" or bifurcation point is always caused by the prevalence of conflictual relations between stakeholders over synergistic ones, while the ending – vice versa (Lysyuk, 2023). The bifurcation point is often associated with the termination of project activities to jointly search for options for further development of the project/programme, considering the stakeholders' own values (Fig. 1). It is objectively impossible for each individual stakeholder to make such a reflection. Problems that accumulate at bifurcation points need to be addressed during programme implementation.

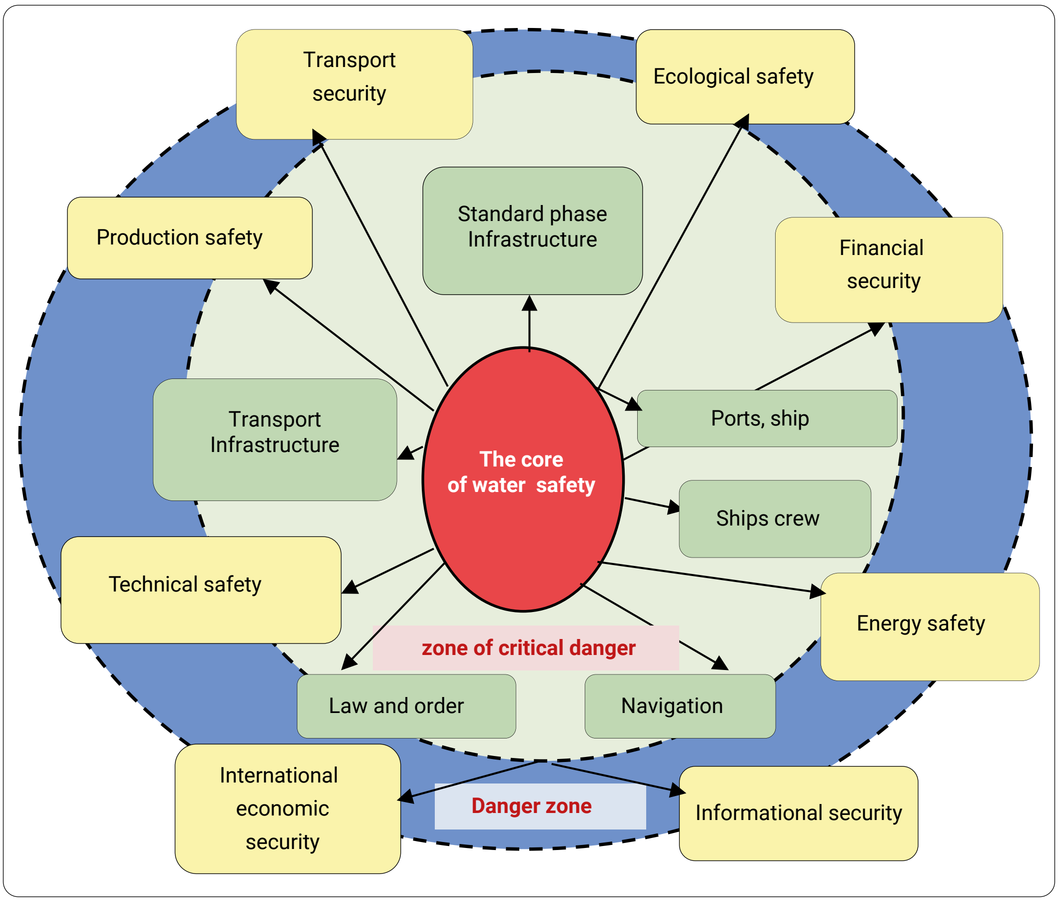

Figure 1. Conceptual model of economic security of transport infrastructure
Source: developed by the author of this study

The change in relations between stakeholders from conflict to synergy at bifurcation points is based on the results of reflection on the project's own, strategic and service values. For this, the programme life cycle is divided into stages according to the number of bifurcation points. At the end of each stage, as one approaches the expected bifurcation point, the results achieved are comprehensively assessed and compared with the targets set for that stage. The principle of phased implementation is based on a clear monitoring, evaluation, and data collection system that allows for tracking changes over time and in line with particular programme objectives (Nikolskyi & Kramskyi, 2020). It is advisable to conduct this analysis at each stage separately for the outputs and outcomes.

3. **Description and implementation of the economic security model for transport infrastructure**

In the monitoring model proposed above, the programme is divided by bifurcation points into stages (depending on the degree of complexity of the programme, there may be more stages, e.g., 4 stages are considered), with n output goals and m main results (in the example above, n = 20, m = 6). The assessment of the programme implementation is formed using a petal chart, on the axes of which the indicators of achievement of the goals and their planned values of indicators are marked during the calculations. It is worth considering how this model works in greater detail. A petal chart of output (Sturgeon, 2009) goals consists of twenty axes that are evenly distributed around a circle and divide it into equal angles, indicating equality in achieving this goal.

The suggested monitoring model, which relies on creating diagrams of initial and final goals in the form of petals, demonstrates the degree of goal achievement at stage *t* relative to the planned level. Based on the results of the assessment of the programme's implementation at the current stage, the next stage of the programme is planned and adjusted. This model of programme management considers not only the internal links between projects but allows responding quickly to changes in the external environment. The reason for this is that at all stages it is possible to adjust activities according to latest changes in the external environment (Infrastructure projects with EBRD and EIB, 2023). Another advantage of the model under study is the ability to conclude whether the programme's objectives are balanced.

If a project involves several phases/industries, etc., a full set of values is generated:

$$Eprojp_M = Vproj_M \times QAim_m \times (1 - AltW_M), \qquad (6)$$

where QA_{imM} is the number of values considered.

If a program affects several phases/branches, etc., a full set of E_{projM} values is generated:

$$Ath_M = Eproj_M \times PTth_M + Kith_M \times A0th_M, \qquad (7)$$

where K_{ithM} is the number of project values considered, $A0_{thM}$ is the allowable costs for the programme and projects.

This algorithmic model was used as the basis for the developed mathematical model, which belongs to the class of nonlinear models and allows managing the parameters of infrastructure project products as part of the programme (Yevdokimova & Zakharchenko, 2021). As a programme is a convoluted organizational operation with the highest degree of uncertainty, both inside and outside, it becomes extremely challenging to monitor, predict and hence regulate relationships within the programme. The essence and specifics of water transport infrastructure projects are defined. The main types of infrastructure projects in water transport have been identified: modernisation of facilities; replacement of facilities; restoration of facilities; development of existing facilities; and creation of new facilities. This product, on the one hand, must satisfy the interests of stakeholders, and on the other hand, the parameters of the project product determine its cost, duration of individual phase stages, etc. Therefore, the study (Tanaka, 2020) built a model for managing infrastructure project parameters for "standalone" infrastructure projects and for two objects interconnected by the project infrastructure.

The integrated project approach is used primarily during the period of economic recovery. This is exactly the case in the post-war period. According to the modern theory, scientists consider the policy of project and programme management, which has a vertical microeconomic nature. This type of project policy has an impact on certain groups of infrastructure actors and is mainly microeconomic in nature. There are several levels of infrastructure projects: from support for the entire infrastructure sector (or region), its sub-sectors, to support for individual enterprises (groups of them). As the level of efficiency increases, the effectiveness of government regulatory measures increases, while the risks of making wrong management decisions increase. The use of the project approach to regulate programming requires a comprehensive combination of system-wide and project-based policy measures in infrastructure aspects. A distinctive feature of project-oriented companies is that they operate through projects and programmes and apply a project-based approach to the implementation of their current production activities. As of 2023, many companies, including maritime transport, can be defined as project-oriented. Therefore, this paper uses the theory of uncertainty and the theory of complex economic systems management: graphical modelling, system analysis, statistical analysis, and economic analysis as a mechanism of own resources to solve the problems of navigation safety, specifically, to investigate transport infrastructure projects.

Discussion

The maritime transport infrastructure includes all buildings, structures, and waterway communication systems of various modes of transport that meet the transportation needs of the population and industry (Danchuk *et al*., 2020). The main task of the regional transport infrastructure can be formulated as providing the necessary conditions for the functioning of the main production sectors and the efficient use of the region's economic potential (Dubnitskyi, 2021). This opinion, expressed by the authors, has general application to transport infrastructure at any level of consideration, city, regional, or national construction. The transport system can be considered as a set of subsystems of different modes of transport, including the Water Transport subsystem, which includes sea and river components. Accordingly, sectoral subsystems can be identified within the transport and transport and logistics infrastructure. According to conventional wisdom, the basic infrastructure of water transport consists of various components, such as waterways, information and navigation equipment, ports and enterprises providing water transport services. Waterways are intended for the movement of vessels and can be natural (rivers, lakes, seas) or artificial (canals, lock rivers with reservoirs, regulated river sections) (Nikolskyi & Kramskyi, 2020). By their very nature, waterways can be divided into inland and outer waterways. External routes include the seas and oceans, which are much deeper and are used primarily in natural conditions. Special aids to navigation or maritime fleets are used only on approaches to coastal landmarks such as lighthouses or in ports that are in shallow waters or at the mouths of large rivers where the depth is insufficient for ships (Vereshchak, 2021b). A special dredging fleet is used to ensure the normal condition of waterways. Ship maintenance and repair is carried out at ship repair facilities. The main purpose of water transport infrastructure is to create conditions for efficient and safe transportation by sea, river, and mixed transport. The infrastructure serving the export potential needs to be modernised, but this also creates investment opportunities. The introduction of intermodal transport and the use of technological solutions to meet Ukraine's diverse import and export needs open more investment prospects (McCormick, 2020).

Ukraine's losses due to Russia's military invasion in terms of maritime resources and infrastructure were estimated in the study by O. Shumilova *et al.* (2023). Research has proved that a significant number of damages to water infrastructure were detected during the conflict. These include interruptions in water supply, surface water pollution, damaged dams, flooded mines, bacteriological contamination, and interruptions in the operation of hydropower plants. The water supply and wastewater treatment systems were also disrupted, affecting facilities, centralised water supply and wastewater treatment plants. Donetsk and Luhansk regions were most affected, with the largest number of incidents in the Siverskyi Donets basin. Other regions, such as Lviv, Ternopil, and Odesa, also recorded impacts on freshwater resources and water infrastructure. Critical water infrastructure, such as the Dnipro River reservoirs, is under threat, posing the risk of flooding and secondary radioactive contamination. It is to be expected that all these losses will require restoration during the post-war period. The model presented in this study can help in this regard, as it allows for more efficient restoration of infrastructure facilities in case of damage, especially when it comes to its maritime component.

The importance of data and their management for improving the efficiency of infrastructure projects is assessed in H. Halttula *et al.* (2020). The researchers emphasise the importance of avoiding sub-optimisation and data fragmentation by creating a unified and integrated project model. Data should be accessible, accurate, and stored in a common repository throughout the project lifecycle to benefit all stakeholders. Planning the data flow from a lifecycle perspective, especially from a maintenance perspective, is essential to addressing data and editing needs. The researchers also suggest using certain specific types of models to manage data more efficiently, which will help to save money and increase the profitability of projects during their economic cycle. Notably, the principles described in this study may also be useful in rebuilding post-war Ukraine. Another methodology for the formation of infrastructure projects was described in G. Aouad *et al.* (1995). The methodology described by the researchers combines two other methods of modelling and data analysis: information engineering and object-oriented analysis and design using computer software/systems engineering (which provides automation of the created models). Although its development began in the 20th century, even now the use of such methods can be effective in the development and implementation of infrastructure projects.

G. Mejia *et al.* (2020) conducted a relevant study. The researchers assessed the reasons why infrastructure development roadmaps in developing countries were often delayed (not implemented on time). Their work has shown that there is currently no consensus among scholars and practitioners on standardising the causes and categories of delays. However, most often the main reason for the failure to implement roadmaps on time was financial difficulties (especially if the country has a low level of GDP (gross domestic product) and global competitiveness index (GCI) and poorly formed contracts). Contractors or subcontractors often caused delays by not performing their obligations: African countries often had difficulties with the supply of equipment and materials. For Asian countries, external influences and difficulties in planning infrastructure project processes were more often the causes of delays. Thus, this paper makes recommendations on how to avoid these issues: they are quite extensive and primarily related to improving the planning processes of various components of project implementation to prevent problems with them in the future. The government of Ukraine should also pay attention to these problems to prevent them from arising during the post-war reconstruction of the country. This is especially true given the importance of this process for the future effective development of the state and its exceptional scale.

Thus, the model proposed in this paper has several advantages, including the ability to assess the balance between the social and production goals of the programme. To achieve maximum efficiency in infrastructure project management, it is also important to consider costs, duration, and stakeholder interests. The mathematical models and algorithms described in the paper above help achieve a more efficient overall satisfaction of the needs of all stakeholders. Using mathematical models and algorithms, it becomes possible to control the parameters of infrastructure project products within the programme, considering factors such as costs, duration, and stakeholder interests. This is because the complexity and uncertainty associated with infrastructure projects require a comprehensive approach to managing relationships within the programme and forecasting changes. Thus, the state should pay much attention to the implementation of infrastructure projects, ensure that the representatives involved in its implementation are sufficiently qualified and that financial flows are managed to ensure their sufficient efficiency for the further functioning of these projects.

Conclusions

The paper emphasised the importance of adopting a monitoring model based on bifurcation points and petal charts for effective management and evaluation of complex infrastructure projects. By dividing the programme lifecycle into stages and regularly assessing the results achieved against planned indicators, project managers can make informed decisions and adjust activities in line with changing external conditions. This approach not only considers the internal linkages between projects but provides the flexibility to respond to a dynamic external environment. Modelling is based on formalised relationships between the cost, time, and other characteristics of a project and its programme parameters. This model defines a set of project parameters within a possible range of changes that maximises the value for stakeholders both during the creation of an infrastructure facility and during its subsequent management (operation).

During this study, a concept was formed, and a model was developed that allows managing the parameters of infrastructure project products within the programme. For dredging projects, models were developed to determine time and product parameters. Models of integrated management and coordination of products and resource allocation for river fleet, port, and inland waterway infrastructure development projects have been built. Experimental calculations were also carried out with varying initial data, including constraints, which substantiated the models' compliance with the logic of product parameter coordination and their impact on project characteristics, as well as the reliability of the results obtained on their basis.

For investigations in the future, it is still relevant to develop other strategies to manage carrying out of infrastructure projects in Ukraine, along with comparative analysis to measure the benefits and drawbacks of each approach. Furthermore, an assessment of foreign practices in this area may be relevant to improve the effectiveness of such models.

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Conflict of Interest

None.

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Концептуальна модель управління фазами реалізації інфраструктурних проєктів та програм у повоєнний час

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Анотація. Початок повномасштабного вторгнення Росії в Україну завдав значних людських, економічних та політичних збитків, а також руйнувань для інфраструктури. Тим не менш, у майбутньому усі отримані втрати мають бути відновленні. Таким чином, актуальним залишається формування моделей управління реалізацією інфраструктурних проектів, зокрема в Україні в її післявоєнних умовах. Метою роботи стало побудувати модель, що дозволила б у майбутньому забезпечити найвищу ефективність управління під час реалізації інфраструктурних проектів у повоєнний час, описати можливості її використання на практиці. Основними методами, що були використані під час проведення дослідження, стали аналіз, моделювання та абстрагування. Таким чином, в рамках дослідження було побудовано концептуальну модель управління за реалізацією інфраструктурних проектів та програм у повоєнний час. Також виконано аналіз сучасної теоретичної бази управління інфраструктурними проєктами, виокремлено проблему обґрунтування параметрів продуктів інфраструктурних програм та проєктів. Описувалися мережеві моделі, їхні особливості та можливості використання для надання більш чіткої картини робіт проекту, більш ефективного управління ресурсами на ньому. У роботі підкреслюється, що інфраструктурні проекти часто поділяють на дві фази: створення та експлуатація; крім того, описується важливість інфраструктурних проектів для ефективних перевезень вантажів і пасажирів та їх вплив на конкурентоспроможність транспортної системи. Дане дослідження дозволяє більш детально зрозуміти особливості управління фазами реалізації інфраструктурних проектів, особливо в умовах повоєнного часу, а також привносить нові знання для менеджменту у розрізі побудови масштабних інвестиційних програм

Ключові слова: економічно-математичні моделі; водний транспорт; економіка України; менеджмент; макроекономіка