





Assessment of Critical Factors in Seaport Digital Transformation Using a Fuzzy Analytical Hierarchy Process


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Abstract: The paper presents a methodological approach to identifying and prioritizing the factors influencing the digital transformation of seaports. Based on an expert survey interpreted through the Fuzzy Analytical Hierarchy Process (Fuzzy AHP), the study consolidates the opinions of specialists representing port administrations, logistics companies, and research institutions. The analysis focuses on four groups of factors — technological, economic, organizational, and institutional — that determine the effectiveness of digital modernization. The results show that technological infrastructure and investment capacity are perceived as the main drivers of transformation, while organizational mechanisms ensure adaptability and coordination of digital processes. Institutional and regulatory support contributes to the long-term sustainability and alignment of digital transformation with national development strategies. The proposed approach provides a structured basis for evidence-based management and the formulation of investment priorities in the sustainable development of smart ports.

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1 INTRODUCTION

Seaports, which facilitate the majority of international trade, play a central role in integration national economies into global supply chains. Its digital transformation (DT) directly impacts on the efficiency of export-import operations and the overall competitiveness of industry.

Recent research demonstrates that the DT of ports goes beyond the scope of the individual technologies implementation and involves the restructuring of organizational, technological, and institutional mechanisms and processes. The usage of digital tools — artificial intelligence, the Internet of Things, and big data analytics — transforms ports into intelligent hubs for management of data and resource flows. However, such transformations are accompanied by constraints related to infrastructure, personnel qualifications, and the regulatory environment.

In the studies of such scientists as Almeida F., Bråthen S., Helgheim B., Karlsson M., Lind M., Raza Z., Sakita B., Sandberg J., Vural C.A., Woxenius J., Blyudik A. R., Masyuk N. N., Niyazbekova Sh. U., Chizhankova I. V., Shepelin G. I., the key factors of seaports digitalization are identified, including the level of digital infrastructure development, investment potential, standardization of business processes, personnel competencies and institutional support from the state (Sakita, Helgheim, Bråthen, 2024; Karlsson, Sandberg, Lind, 2023; Almeida, 2023; Raza, Woxenius, Vural, Lind, 2023; Shepelin, Chizhankova, Niyazbekova, 2023; Masyuk, Blyudik, 2022).

The combination of these factors forms the systemic foundation of the port sector's digital maturity, determining the speed and depth of technological transformation. However, most studies remain focused only on a qualitative description of factors, which prevents from determining its significance in the context of DT and setting priorities according to which this process planning should be done. However, effective planning and prioritization, largely determine the effectiveness of DT activities.

In this regard, there is a need to conduct a quantitative assessment of the factors significance which influence on the DT effectiveness of port systems, in conditions of limited access to classified information, which determines the research methodology.

2 METHODS AND MATERIALS

The purpose of the study is to assess the relative importance of key factors, which influence on the seaports DT and to determine its priority for the strategic management of the port system digital modernization process based on the fuzzy analytical hierarchy process (Fuzzy AHP).

Research objectives:

1. To systematize the basic factors of the seaports DT across key areas: technological, economic, organizational, institutional, and personnel.

2. To conduct an expert assessment of the factors and transform the experts' linguistic judgments into quantitative fuzzy estimates.

3. To apply the Fuzzy AHP method to calculate the relative importance of the factors and rank them based on their impact on the port's digital maturity.

4. To prioritize management impact and investment directions to improve the effectiveness of the seaport system DT.

The initial stage of the study was an expert survey conducted at seaports, aimed at identifying key factors in the DT, as well as determining the five groups of factors influence — technological, economic, organizational, institutional, and personnel — on the success of the seaports DT.

An expert survey conducted from November 2023 to August 2024 among 15 qualified professionals representing seaport administrations, logistics and IT companies, and research organizations. All questionnaires were deemed reliable and included in processing. The average professional experience of the participants was 11 years (range: 6 to 22 years).

Interdisciplinary collaboration between professional communities, combining technical, managerial, economic, and regulatory expertise, allowed us to develop a systemic understanding about the priorities for DT in the port industry. This approach ensured a comprehensive understanding of digitalization not as an isolated technological process, but as a multi-layered mechanism for structural changes, involving technical modernization, organizational development, and institutional adaptation.

The ports of St. Petersburg, Novorossiysk, and Vladivostok, which provide the majority of Russia's industrial exports, were chosen as the study subjects. The differences in organizational structure and level of digital maturity between these ports necessitated the Fuzzy AHP usage, which enables the comparison and ranking of factors based on its

impact on the effectiveness of the port system's DT. In accordance with this methodology, an expert group was formed that combined analytical and practical expertise, which ensured the reliability and reproducibility of the results obtained.

3 RESEARCH

Contemporary research (Cheng, Chen, Chuang, 2008; Alqahtani, Noman, 2024; Ok, Altın, Celik, 2024; Martins, Fornari Junior, 2023) confirms that expert procedures based on the Fuzzy Delphi and Fuzzy AHP methods are an effective tools for harmonizing multi-level knowledge and minimizing uncertainty in the assessment of complex socio-technical systems. The logic for forming factor's groups and the research stages are presented in Table 1.

Table 1: Stages of expert evaluation process.

Stage	Description	Result
1	Identifying key factors influencing the digital transformation of seaports	5 large groups of criteria have been defined
2	Construction of a hierarchical structure (group of factors)	The system of criteria for paired comparisons has been developed
3	Conducting an expert survey	Qualitative assessments of the significance of factors have been obtained
4	Estimates transformation into fuzzy numerical values and its aggregation	Relative priorities of factors have been determined
5	Weights normalization and consistency checking	The final values of the factor weights have been obtained

In the first stage of the study, based on an analysis of the results of the expert survey first part, a set of factors influencing on the seaport DT efficiency were identified. During aggregating the respondents' opinions, all identified determinants were grouped into four broad areas: technological, economic, organizational, and institutional (Table 2).

Table 2: The group of factors affecting the effectiveness of digital transformation of seaports

Group of factors	Description
Technological	IT infrastructure; IoT and sensor networks; cybersecurity; integration of smart port platforms; data

	standardization and interoperability
Economic	Availability of investments; cost structure of digital projects; return on investment; private capital participation; economic efficiency of digitalization
Organizational	Flexibility of management structure; readiness of internal processes for digital change; existence of digital transformation units; coordination among port cluster participants
Institutional	Governmental support of digitalization; regulatory and legal framework; compliance with national standards; policy alignment at national and regional levels

This structuring provided a holistic understanding of the multi-level nature of DT in the port system.

At the same time the expert survey utilized a four-level linguistic scale ("yes," "more yes than no," "more no than yes," and "no"). Each linguistic expression corresponded to a triangular fuzzy interval, characterizing the range of possible preference values. This procedure allowed us to reflect not only the average judgment but also the degree of variability (Table 3). This approach enables factors quantitative comparison without overloading experts with complex pairwise comparisons, while preserving the ambiguity of their judgments.

Table 3: Example of interpreting an expert survey.

Linguistic term	Interpretation	Triangular fuzzy number (L, M, U)
No	The factor has no significant influence	(0.00, 0.00, 0.25)
Rather no than yes	Weak or occasional influence	(0.15, 0.35, 0.55)
Rather yes than no	Moderate or substantial influence	(0.45, 0.65, 0.85)
Yes	Strong or decisive influence	(0.75, 1.00, 1.00)

The integration of expert judgments into a fuzzy model made it possible to transform linguistic assessments into quantitative ones and identify key groups of factors that shape the DT effectiveness.

In the next step, this scale was applied to assess the impact of each factor's group on the effectiveness of the seaport's DT. Table 4 presents an example of aggregated responses, demonstrating the transition from linguistic assessments to their fuzzy numerical equivalents, which ensured the

consolidation of the experts positions from various fields.

Table 4: Example of aggregated expert responses.

Group of factors	Expert response	Fuzzy value (L, M, U)
Technological	Yes	(0.75, 1.00, 1.00)
Economic	Rather yes than no	(0.45, 0.65, 0.85)
Organizational	Rather no than yes	(0.15, 0.35, 0.55)
Institutional	Yes	(0.75, 1.00, 1.00)

After aggregating individual expert assessments, averaged fuzzy values were obtained for each factor group. For further analysis and comparison of its significance, a defuzzification procedure was performed, converting the triangular fuzzy numbers into crisp values based on a formula.

At the stage of aggregating expert assessments, each group of factors was represented as a fuzzy triangular number:

$$\tilde{A} = (L, M, U)$$

where:

L — lower value of the estimate (minimum possible value),

M — modal (most probable) value,

U — upper value of the estimate (maximum possible value).

The study used the most common formula for defuzzification of triangular fuzzy numbers — the center of gravity method.

$$\tilde{A} = \frac{L + M + U}{3}$$

If, according to the results after aggregation, the group of factors “Technological” had a value:

$$\tilde{A}_{tech} = (0.75, 1.00, 1.00)$$

Then after defuzzification:

$$\tilde{A}_{tech_{defuzz}} = \frac{0.75 + 1.00 + 1.00}{3} = 0.92$$

The values for the remaining groups of factors are calculated in a similar manner, after which normalization and approval of its priority ranking are carried out.

This enabled a possibility for quantitative ranking of factors based on its impact on the

effectiveness of seaport DT. The defuzzification results are presented in Table 5.

Table 5: Relative importance of factor groups in seaport digital transformation.

Group of factors	Weight
Technological infrastructure	0,27
Economic	0,21
Personnel	0,19
Organizational	0,17
Institutional	0,16

The resulting standardized weights reflect the collective opinion of the expert community about the technological, economic, organizational, personnel, and institutional factors in forming the digital maturity of a port system and form a quantitative basis for interpreting the results.

Technological infrastructure received the highest share (0.27). Experts emphasized that the state of the digital infrastructure — the availability of integrated information platforms, automated control systems, stable data transmission channels, and cybersecurity mechanisms — forms the foundation of a port's digital maturity. Without technological readiness, it is impossible to ensure process transparency, prompt information exchange, and coordination among logistics network participants.

Economic factors rank second in importance (0.21). Its influence is determined by the port's ability to attract resources, evaluate the effectiveness of implemented solutions, and ensure a return on investment. Financial stability and the existence of long-term development programs create the conditions for the consistent and controlled implementation of digital technologies.

Human resources factors rank third (0.19). DT is impossible without specialists capable of combining technical and managerial competencies. A lack of trained personnel and limited opportunities for professional development often act as constraints, slowing innovation implementation. However, the presence of teams focused on digital change significantly accelerates the transformation process.

Organizational factors rank fourth (0.17). Its role is to ensure coordination between departments, standardize processes, and manage data effectively. Even with advanced technology, low levels of organizational coordination lead to decreased efficiency.

The institutional and regulatory environment (0.16) ranks last on the list, but it is an important factor in terms of the sustainability of transformation. Unified standards, transparent rules for information

exchange, and consistent public policy create a predictable framework for the long-term development of digital ports.

The obtained results allow us to formulate a logical sequence of management actions aimed at increasing the efficiency of the port industry DT.

The first stage requires focusing on planning technological modernization, including assessing the potential for implementing a unified digital port platform, automating operations, and developing predictive analytics and cybersecurity systems. These solutions create the foundation for further integration of transport and logistics chain participants and reducing transaction costs.

In the second stage, following the analysis of the DT's technological potential, priority attention is given to the economic justification and preliminary assessment of the effectiveness of future digital initiatives. At this stage, the methodological foundations for investment planning are developed, key performance indicators (KPIs) are defined, a baseline for subsequent comparison is established, and digital asset value management tools are developed. This approach allows us to assess the feasibility of digital solutions even before its implementation, predict expected effects, and ensure rational resource allocation during the transformation stages.

The next direction for planning is the human and organizational potential development: staff training, the development of digital competencies, the implementation of change management systems and data management standards.

At the final stage, the most important conditions for the DT sustainability are the improvement of regulatory acts, the support for industry standardization and the development of public-private partnership tools.

Thus, the ports DT should be considered not as a set of individual IT projects, but as a coherent strategy that combines technological, economic and organizational transformations into a unified development management system.

4 CONCLUSION AND DISCUSSION

The study identified, systematized, and rated the relative importance of DT efficiency factors using the Fuzzy Multi-Criteria Evaluation (Fuzzy AHP) method. The results demonstrate that digitalization effectiveness is determined by a combination of

technological, economic, human resources, organizational, and institutional factors, the interaction of which forms a holistic «smart port» ecosystem.

Each of the studied factors groups influences the dynamics and quality of DT. Technological infrastructure and investment resources serve as the foundation of transformation, ensuring the functionality and sustainability of digital solutions. Organizational and personnel components set the pace and manageability of change, while the institutional environment creates the regulatory and coordinating framework for its sustainable implementation. This interconnectedness highlights the systemic nature of DT, where success is determined not by the implementation of individual innovations, but by the integration degree of the undertaken changes in various factors into a unified development strategy.

The feasibility and scientific significance of the Fuzzy AHP method (Yang, Hsieh, 2024) for analyzing complex socio-technical systems has also been confirmed, as it creates a formalized basis for collecting data to align expert opinions and make managerial decisions. This method ensures a balance between expert knowledge and formalized data processing, creating a reproducible foundation for managerial decision-making based on changes of various types. Its application in research of seaport infrastructure DT allows not only to identify the determinants of DT but also to determine the logic of the institutional and technological changes which are necessary for the transition to a sustainable digital development model.

It should be mentioned that the proposed assessment approach is based on the results of an expert survey and reflects the perception of digitalization factors at the time of the study. While this approach allows analyzing qualitative relationships in-depth, it does not capture quantitative indicators of efficiency such as productivity, energy intensity or cargo handling speed. In the future, it would be advisable to supplement the proposed model with empirical data reflecting the actual results of port operations digitalization and conduct a dynamic comparison across different regions and port types.

The practical significance of the results lies in its potential usage in digital development strategies developing for the port sector. The resulting priorities form the basis for developing DT roadmaps, identifying investment priorities, and allocating resources between technological and organizational areas. They also enable an assessment

of ports' readiness for integration into national and international digital logistics platforms, thereby increasing the transparency and manageability of the entire transport and industrial system.

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