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Digital transformation of port activities in the context of investment-driven development of water transport

Abstract. The global maritime sector shifted from traditional port modernisation to systemic digital integration, which required new economic frameworks to justify smart technology investments while ensuring financial security. The purpose of the study was to substantiate the methodological foundations of the digital transformation of port activities in the context of investment-driven development of water transport. The research employed a comprehensive methodological approach, including system analysis, comparative and structural analysis, and economic-statistical modelling to assess investment efficiency through cash flow indicators, profitability, and risk evaluation. The findings demonstrated that digitalisation functioned as a multidimensional economic driver, reducing administrative and documentation costs by 20-30%, vessel turnaround time by up to 25%, and cargo dwell time by approximately 40%. The study proposed an enhanced investment appraisal methodology integrating Real Options Valuation to account for strategic flexibility and introduced a digital premium that adjusted the discount rate based on increased operational transparency. A key innovation was the incorporation of a technological lag coefficient into payback period calculations, aligning capital recovery with the shorter cycle of digital obsolescence. The results indicated that digital investments generated non-linear returns through increasing returns to scale as more stakeholders joined the ecosystem, enabling shorter payback periods and self-financing cycles. Furthermore, the study conceptualised a mechanism for integrating digitalisation effects into the port's financial security architecture, proving that technological transparency and operational velocity serve as critical reserves for institutional resilience. The classification of digital risks into technological, financial, and cyber clusters allowed for a risk-oriented evaluation where investment projects were filtered through a security threshold to prevent systemic fragility. The practical value of the work lay in the developed tools for the economic justification of smart port projects, which enabled port operators and investors to accurately model incremental effects, optimise capital structure, and strengthen the financial security of water transport infrastructure in a digitalised global environment

Keywords: transport and logistics systems; port infrastructure development; investment efficiency; operational costs; cash flow management; risk assessment; financial and economic security

INTRODUCTION

The rapid transformation of global trade and logistics systems has significantly increased the strategic importance of port infrastructure as a critical node in international supply chains. Under conditions of growing uncertainty,

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geopolitical instability, and increasing requirements for efficiency and sustainability, traditional approaches to port development were becoming insufficient. The transition from physical infrastructure expansion to digital integration was no longer optional but represented a fundamental shift in the economic logic of port development. However, while digital technologies created new opportunities for improving operational performance, they simultaneously generated complex investment challenges related to risk, uncertainty, and the need to ensure financial and economic security. A key problem lay in the inconsistency between the dynamic nature of digital transformation and the inertia of traditional investment evaluation approaches. Existing methods for assessing infrastructure projects were primarily designed for long-term, capital-intensive assets with predictable life cycles, whereas digital technologies were characterised by rapid obsolescence, high uncertainty, and non-linear economic effects. This created a methodological gap in the economic justification of investments in port digitalisation, particularly in terms of integrating risk factors, evaluating financial performance, and ensuring system resilience.

Scientific literature extensively examined the impact of digital transformation on port performance and maritime logistics systems. E. Tijan *et al*. (2021) investigated the role of digital technologies in maritime transport and concluded that automation, artificial intelligence, and blockchain significantly transform operational processes and enable new models of value creation. S. Adabere *et al*. (2021) analysed the relationship between information technology adoption and port performance, demonstrating that digital tools contribute to increased efficiency through process optimisation and reduction of operational delays. G. Boakye *et al*. (2021) focused on data-driven approaches in port management and established that the use of analytical models enhances productivity and decision-making quality. M. Karlsson *et al*. (2023) explored the drivers and barriers of digitalisation in port environments and identified institutional, technological, and organisational constraints that limit the adoption of digital solutions, particularly insufficient investment and regulatory challenges. P.W. de Langen (2023) developed a conceptual framework of port development based on business ecosystems, highlighting the role of digital platforms in coordinating stakeholders and generating value. Z. Su (2026) examined the formation of digital ecosystems in port logistics and demonstrated that integration of digital technologies improves coordination and overall system performance. The investment dimension of digital transformation has also been addressed in recent studies. T. Notteboom *et al*. (2021) analysed the impact of global disruptions on port systems and emphasised the need for investments in digital technologies to enhance resilience and adaptability. M. Mollaoglu & M. Gul (2025) investigated the relationship between digital transformation strategies and investment decision-making, concluding that digitalisation significantly influences long-term competitiveness in maritime transport. O.-P. Brunila *et al*. (2021) studied the implementation of advanced technologies such as 5G in smart ports and identified both opportunities and infrastructural constraints affecting investment efficiency. T. Koritarov & D. Dimitrakiev (2025) substantiated that digitalisation is a key factor in improving the efficiency, sustainability, and competitiveness of modern ports.

In the context of increasing uncertainty and systemic risks, particular attention has been paid to the issues of resilience and security. A.K.Y. Ng *et al*. (2025) analysed the role of digital technologies in enhancing the resilience of maritime transport systems and demonstrated that digital solutions improve adaptability and risk assessment capabilities. G.V. Iefimova & O.V. Pashchenko (2025) examined the financial and economic security of port activities and concluded that digital transformation requires the integration of risk-adjusted approaches to investment evaluation and new criteria for ensuring financial and economic security. Despite the significant number of studies, the existing literature mainly focuses on either technological aspect of digitalisation or general issues of port development. At the same time, there is a lack of comprehensive methodological approaches that integrate digital transformation factors into the economic justification of investments, taking into account financial performance indicators, risks and security aspects. This determines the need for further research in this area. The purpose of the article was to substantiate the theoretical and methodological foundations of digital transformation of port activities in the context of investment-driven development of water transport and to develop a methodological approach to the economic justification of investments in port digitalisation, considering financial performance indicators, technological uncertainty, digital risks and security aspects.

MATERIALS AND METHODS

This study was based on a comprehensive methodological approach aimed at analysing the digital transformation of port activities in the context of investment-driven development of water transport. The research design combined theoretical generalisation, comparative analysis, and elements of economic modelling to ensure consistency and reproducibility of the results. The research process included several interconnected stages. At the initial stage, the problem was identified and global trends in the development of water transport and port infrastructure were analysed based on international analytical and statistical sources, including reports by the European Commission (n.d.), the World Bank (2025) and United Nations (2025) which provided a systematic overview of current challenges in maritime logistics and port digitalisation. To define the policy and institutional context of port digitalisation, the study also considered national and international strategic documents. In particular, the Danish Maritime Authority (n.d.) was used to identify how national maritime policy links digital technologies with efficiency improvement and sustainable development. The position of the International Maritime Organisation (2025) was analysed to determine the global priorities of maritime digitalisation, including safety, environmental performance and operational efficiency. In addition, OECD (2020) materials were used to place port digital transformation within broader digital economy trends, where data-driven technologies influence value creation, investment decisions and sectoral development. This stage allowed for the identification of key structural changes in maritime logistics, including increasing digitalisation, supply chain disruptions, and the growing role of data-driven management.

The next stage involved the systematisation of methodological approaches relevant to the evaluation of port performance, investment efficiency, and digital transformation. In particular, multi-criteria approaches to port performance assessment were considered based on V. Lorenčič *et al*. (2022), which allowed for the identification of key performance dimensions beyond purely financial indicators. In addition, recent empirical studies on digital maturity and organisational performance, such as K.C. Shang *et al*. (2026), were used to incorporate the concept of dynamic capabilities and non-linear efficiency effects into the analytical framework. These approaches were selected because traditional models of investment evaluation do not sufficiently account for the complexity, uncertainty, and rapid technological change associated with digitalisation. Based on this, a methodological framework for the economic justification of investments in the digital transformation of port activities was developed. This framework integrates traditional investment appraisal tools with elements that reflect the specific characteristics of digital technologies, including shorter life cycles, higher uncertainty, and non-linear returns. The proposed approach combines traditional financial indicators, including net present value (NPV), internal rate of return (IRR), payback period (PP), and cash flow modelling, with additional digitalisation-specific parameters such as the digital premium, technological lag coefficient, and risk-adjusted discount rate. The assessment methodology also incorporates elements of real options valuation (ROV) to account for strategic flexibility and future technological expansion opportunities. The evaluation procedure was carried out using comparative analysis, economic-statistical modelling, scenario-based assessment, and risk analysis methods. Quantitative evaluation included the estimation of incremental revenues, operational cost savings, logistics efficiency indicators, and discounted cash flows, while qualitative assessment focused on operational transparency, resilience, interoperability, and cyber-security risks.

A set of general scientific and special methods was applied in the study. System analysis made it possible to consider port infrastructure as an integral element of transport and logistics systems and to identify the interrelations between digitalisation, investment processes and operational performance. Comparative and structural analysis were used to evaluate the impact of digital technologies on cost structure, port operations and efficiency indicators. Economic and statistical methods were applied to assess investment efficiency through indicators of cash flows, profitability and cost optimisation. In addition, methods of abstraction and generalisation were used to develop a unified methodological approach, while risk analysis methods allowed the identification and classification of key risks associated with digital transformation. The analytical assessment of the proposed methodological framework was carried out using a system of quantitative and qualitative criteria. Quantitative evaluation included the calculation and interpretation of standard financial indicators, such as net present value NPV, IRR, payback period, and changes in operating costs and revenue streams resulting from digitalisation. Qualitative assessment was based on criteria such as the level of operational transparency, improvement of coordination between stakeholders, service quality enhancement, and the ability to increase system resilience. In addition, risk-adjusted evaluation criteria were applied, taking into account uncertainty, variability of cash flows, and potential technological obsolescence. The empirical basis of the study relies on secondary data obtained from international analytical reports, statistical materials, and scientific publications in the field of maritime transport and logistics, including United Nations (2025), World Bank (2025), and recent peer-reviewed studies. This ensures the reliability, comparability, and relevance of the results. The use of generally accepted analytical tools and accessible data sources allows the proposed methodology to be replicated in different contexts, confirming its scientific validity and practical applicability.

RESULTS AND DISCUSSION

Impact of digitalisation on costs, port charges and logistics efficiency

Digital transformation of port activities represented a complex and multidimensional process that involves the integration of advanced information and communication technologies into operational, managerial and logistical processes. In the context of water transport development, digitalisation was defined as the systematic implementation of digital solutions aimed at increasing efficiency, reducing costs, enhancing transparency and improving the coordination of transport and logistics systems. Unlike traditional modernisation, digital transformation implied not only technological upgrades but also structural changes in business models, decision-making processes and interaction between stakeholders. Modern ports were increasingly evolving into so-called “smart ports”, where digital technologies ensured real-time data exchange, automation of operations and optimisation of resource use. As noted by E. Tijan *et al*. (2021), digital transformation significantly enhanced the efficiency of maritime transport systems by enabling data-driven management and integration of logistics chains. At the same time, Z. Su (2026) emphasised that digitalisation contributes to the formation of integrated digital ecosystems, where ports act as key nodes connecting various participants of global supply chains.

Among the key technologies that formed the basis of digital transformation in port activities, the Internet of Things (IoT) played a crucial role. IoT enabled the collection and transmission of real-time data from physical objects such as containers, cargo handling equipment and transport vehicles. For example, the implementation of sensor-based monitoring systems in ports allows tracking the location and condition of cargo, reducing delays and minimising losses. According to S. Adabere *et al*. (2021), the use of such technologies significantly improved operational efficiency and reduced idle time in seaports. Another important technological component was Big Data analytics, which allowed processing large volumes of structured and unstructured data generated by port operations. The use of Big Data enabled forecasting cargo flows, optimising port capacity utilisation and improving decision-making processes. For instance, ports that applied predictive analytics can better manage peak loads and reduce congestion, thereby lowering operational costs. The importance of data-driven decision-making in port management is also highlighted by M. Karlsson *et al*. (2023), who identified data availability and analytical capabilities as key drivers of digitalisation.

AI further expanded the possibilities of digital transformation by enabling automation and intelligent optimisation of complex processes. AI technologies are used in ports for demand forecasting, automated scheduling of cargo handling operations and optimisation of logistics routes. In practice, AI-based systems can dynamically allocate resources depending on real-time conditions, increasing overall efficiency. As noted by K.C. Shang *et al*. (2026), the integration of AI into maritime transport systems was closely linked to the development of dynamic capabilities and improvement of organisational performance. Blockchain technology was another important element of digital transformation in port activities, particularly in ensuring transparency and security of transactions. Blockchain enabled the creation of decentralised and tamper-proof databases for recording transactions and tracking cargo movements. For example, the use of blockchain platforms in port logistics allowed reducing paperwork, accelerating customs procedures and minimising the risk of fraud. According to E. Tijan *et al*. (2021), blockchain significantly improved trust among supply chain participants and enhanced the efficiency of information exchange. In addition to individual technologies, the combined application of IoT, Big Data, AI and blockchain created a synergistic effect, transforming ports into integrated digital platforms. Such integration allowed not only improving operational performance but also creating new opportunities for investment and innovation. However, as highlighted by M. Karlsson *et al*. (2023), the implementation of these technologies required significant financial resources and faced barriers related to infrastructure, regulation and organisational readiness. The diversity and complexity of digital solutions in port environments were systematised in recent smart port studies, which highlighted the multidimensional nature of digital transformation and the interconnection between technological, organisational, and sustainability domains (Belmoukari *et al*., 2023). Thus, digitalisation in port activities was a key factor in increasing the efficiency and competitiveness of water transport systems. The use of advanced digital technologies not only transformed operational processes but also created a foundation for sustainable investment development and long-term growth of port infrastructure. The integration of digital technologies into port activities generated measurable economic effects, particularly in terms of cost reduction, optimisation of port charges and improvement of logistics efficiency. The obtained results confirmed that digital transformation acts as a key factor in increasing operational performance and investment attractiveness of port infrastructure.

Empirical evidence indicated that the implementation of digital solutions contributes to a significant reduction in operational costs. According to the World Bank (2025), the use of port community systems and automated data exchange platforms reduced administrative and documentation costs by approximately 20-30%. Similar results were reported by E. Tijan *et al*. (2021), who noted that automation of cargo handling processes and the use of digital tracking systems reduced vessel turnaround time by up to 25%, which directly affected port operating expenses. In addition, the application of IoT-based monitoring systems enabled predictive maintenance of equipment, reducing maintenance costs by around 10-15% (Adabere *et al*., 2021). The impact of digitalisation on port charges was primarily indirect and was manifested through increased transparency and optimisation of tariff structures. Digital platforms allowed for real-time calculation of port fees based on actual service usage, reducing inefficiencies and hidden costs. According to the European Commission (n.d.), the implementation of digital billing and integrated information systems contributed to a reduction in transaction costs by approximately 15-20%. At the same time, the standardisation of procedures and the reduction of administrative barriers led to a decrease in total logistics costs for port users.

The effect of digital transformation on logistics efficiency was particularly significant. The use of Big Data analytics and artificial intelligence allowed for optimisation of cargo flows, reduction of congestion and improvement of resource allocation. For example, ports implementing advanced data analytics systems demonstrated an increase in cargo throughput efficiency by 10-20% (Karlsson *et al*., 2023). This was also consistent with (Kotenko *et al*., 2022), who emphasised the role of transport infrastructure efficiency and transit potential in enhancing logistics performance under conditions of economic transformation. These findings were also consistent with studies demonstrating that improvements in port connectivity and logistics performance have a significant positive impact on trade efficiency and economic growth (Liang & Liu, 2020). Furthermore, blockchain technologies contributed to the acceleration of document processing and customs clearance procedures, reducing cargo dwell time by up to 40% (Tijan *et al*., 2021). The quantitative results of the impact of digitalisation on key performance indicators of port activities were summarised in Table 1.

Table 1. Impact of digitalisation on key economic indicators of port activities

Indicator	Effect of digitalisation	Average change, %
Operational costs	Decrease	20-30
Maintenance costs	Decrease	10-15
Transaction (administrative) costs	Decrease	15-20
Vessel turnaround time	Decrease	up to 25
Cargo dwell time	Decrease	up to 40
Logistics efficiency (throughput)	Increase	10-20

Source: compiled by the authors based on European Commission (n.d.), E. Tijan *et al.* (2021), S. Adabere *et al.* (2021), M. Karlsson *et al.* (2023), World Bank (2025)

The presented results demonstrated that the economic effects of digitalisation are multidimensional and mutually reinforcing. Cost reduction was achieved through automation and optimisation of processes, while improvements in logistics efficiency led to increase throughput and better utilisation of port infrastructure. At the same time, the reduction of transaction costs and increased transparency contributed to the optimisation of port charges and enhanced the overall investment attractiveness of ports. In comparison with existing studies, the obtained results were consistent with the findings of M. Mollaoglu & M. Gul (2025), who emphasised the role of digital transformation in improving operational efficiency and reducing costs in maritime transport. Similarly, T. Notteboom *et al*. (2021) underlined that digitalisation enhances the resilience and adaptability of port systems, particularly under conditions of global disruptions. However, unlike previous studies, the presented results provided a more integrated assessment of the economic effects of digitalisation by simultaneously considering costs, port charges and logistics efficiency within a unified analytical framework.

At the same time, the results raised several discussion issues. Despite the positive economic effects, the implementation of digital technologies required significant initial investments, which may limit their adoption, especially in developing port systems. In addition, the uneven level of digital maturity across ports created disparities in efficiency and competitiveness. As noted by O.-P. Brunila *et al*. (2021), infrastructural and technological barriers remained significant constraints for large-scale digital transformation. In addition, institutional and regulatory factors, including the role of state support in transport system development, remained critical, as noted by (Lutsenko, 2021). Thus, digitalisation had a substantial impact on the economic performance of port activities, contributing to cost reduction, optimisation of port charges and increased logistics efficiency. These findings confirmed the strategic importance of digital transformation as a key driver of investment development in water transport, while also highlighting the need for further research on balancing costs and benefits of digital investments.

Methodological approach to the economic justification of investments in port digitalisation

The development of a comprehensive methodological approach to the economic justification of investments in digital transformation was a critical step in ensuring the sustainable development of water transport. Unlike traditional infrastructure projects, digital investments were characterised by a high degree of intangible benefits and systemic effects that require a specific set of evaluation tools. The proposed approach was based on the integration of classical investment appraisal methods with the quantification of operational shifts derived from the implementation of smart technologies.

The central element of this methodology was the transition from simple cost accounting to the modeling of incremental effects. The system of indicators was structured to reflect the life cycle of digital solutions and their impact on the port's financial position. A key component of this approach was the modelling of cash flows, where the fundamental metric was the net cash flow generated specifically by the digitalisation project. In the context of port activities, the annual cash flow (CF_t) is defined as:

$$CF_t = (\Delta R_t + \Delta S_t) - (OC_t + M_t + T_t), \quad (1)$$

where ΔR_t – incremental revenue from increased throughput and new digital services; ΔS_t – cost savings (energy, labour, administrative expenses); OC_t – ongoing operational costs of the digital system; M_t – maintenance and software update costs; T_t – costs of personnel training and adaptation.

To justify the long-term viability of digital investments, particular attention was given to profitability indicators, including NPV and IRR, which must account for the specific "digital premium", defined as a reduction in the risk-adjusted discount rate due to increased operational transparency. This evaluation was further enhanced through the integration of Real Options logic, recognising that initial digital investments create a strategic foundation for future technological expansion without significant additional capital expenditures. Empirical evidence from global smart ports suggested that incorporating digitalisation effects into NPV calculations often reveals that projects appearing marginal in terms of direct revenue become highly attractive when considering total cost optimisation and reduced information asymmetry for stakeholders (Karlsson *et al.*, 2023; World Bank, 2025). In this context, the recalculation of IRR reflected not only direct cost savings but also an increase in the asset turnover ratio, which served as an indicator of digital maturity and long-term financial resilience.

Given the rapid obsolescence of digital technologies, the PP becomes a critical constraint, requiring a transition from static models to a risk-adjusted approach. The proposed methodology demonstrated that digital transformation significantly shortens the payback period by accelerating cargo processing, as evidenced by the reduction of operational procedures from hours to seconds in Tianjin Port (Su, 2026). At the same time, the recovery process is characterised by non-linearity due to increasing returns to scale within digital ecosystems. To ensure financial resilience, a "technological lag coefficient" is incorporated into the payback period calculation, allowing investment recovery to be benchmarked against the shorter 3-5-year cycle of digital obsolescence rather than the long-term life cycle of physical infrastructure. This acceleration contributes to the formation of a liquidity cushion and enables self-financing cycles, where rapid capital recovery from initial digital modules, such as automated gate systems, generated internal resources for subsequent technological integration, thereby reducing dependence on external financing and strengthening the overall financial and economic security of the port.

To address the limitations of traditional investment appraisal, the methodological framework was expanded through the integration of several specialised conceptual components. The first component involved the incorporation of the real options valuation concept, aimed at overcoming the constraints of traditional net present value, which tends to underestimate digitalisation by treating investments as linear and fixed. In this study, digital transformation is conceptualised as the creation of a "digital foundation" for future innovations. Accordingly, the classical NPV approach was supplemented with the ROV method, allowing for the consideration of strategic flexibility. Initial investments in digital platforms generated an "option to expand", enabling the subsequent implementation of advanced technologies, such as autonomous transport systems or blockchain-based smart contracts, without significant additional capital expenditures. This substantially increased the overall strategic value of investment projects compared to baseline scenarios.

Another important element of the framework was the adjustment of the discount rate through the concept of "data transparency". The digital premium was formalised by establishing a link between the quality of operational data and financial risk. The implementation of IoT technologies and real-time monitoring systems reduced information asymmetry for investors, thereby improving the transparency of operational processes. This allowed for the decomposition of the discount rate by isolating a digital transparency coefficient, which led to an increase in the project's internal rate of return not only due to higher cash inflows but also due to a reduction in the risk premium associated with operational opacity. A further component of the methodology was the integration of externalities into cash flow structures. Digitalisation often generates immediate financial benefits for port users, such as shipowners, through reduced vessel turnaround time and improved service efficiency. Although these effects were not directly reflected in the port's revenues, they were transformed into competitive advantages over time, contributing to increased customer loyalty and market share. Within the proposed approach, such indirect financial effects were incorporated into the NPV model, allowing ports to apply more flexible pricing strategies and attract technologically advanced carriers, thereby ensuring long-term stability and predictability of cash flows.

The final component concerned the introduction of dynamic payback thresholds and the mitigation of "technological lag". This element moved beyond the static calculation of the payback period toward a risk-adjusted model that accounts for the life cycle of digital assets. Given that digital software and hardware have a significantly shorter life cycle, typically ranging from 3 to 5 years, compared to physical infrastructure such as berths with a lifespan of 20 to 50 years, it is proposed to integrate a technological lag coefficient into the PP calculation ("digital obsolescence" buffer). This implies that the target payback period for digital investments should be strictly shorter than the expected cycle of the next technological upgrade. By accelerating throughput, for example reducing operational processes from hours to seconds as observed in Tianjin Port, digitalisation creates a "liquidity cushion" that enables the port to recover invested capital before the technology becomes obsolete.

At the same time, digital payback was characterised by cumulative efficiency rather than linear recovery. Unlike traditional infrastructure, which generated relatively constant marginal utility, digital systems demonstrated increasing returns to scale. As more stakeholders, including carriers, customs authorities, and terminal operators, became integrated into the digital ecosystem, the speed and efficiency of cargo processing increased exponentially, resulting in a compressed payback period at later stages of implementation. These transformations also corresponded to the shift toward customer-oriented and flexible logistics service models described by M. Hryhorak *et al*. (2020). Furthermore, the proposed approach considered the shortened payback period of digital projects as a mechanism for internal self-financing. Rapid capital recovery from initial digitalisation initiatives, such as automated gate systems, generated immediate liquidity that can be directed toward subsequent stages, including more advanced solutions like AI-driven berth planning. This created a "virtuous cycle" of investment, reducing dependence on costly long-term external financing and strengthening the overall financial and economic security of port operations.

The generalised results presented above can be further reinforced through an empirical illustration demonstrating the practical application of the proposed methodological framework. To this end, it was considered a stylised yet empirically grounded example of implementing a port community system (PCS) in a mediumsized seaport. This example provided a clear representation of how incremental effects, the "digital premium", and the logic of real options valuation collectively influence the economic assessment of digital investments. According to international studies referenced earlier, PCS implementation led to a 20-30% reduction in administrative and documentation costs, a decrease of up to 25% in vessel turnaround time, and a reduction of up to 40% in cargo dwell time, while predictive maintenance enabled by IoT technologies lowers equipmentrelated expenditures by 10-15% (European Commission, n.d.; Adabere *et al*., 2021; World Bank, 2025). Based on these empirically verified indicators, the modelled investment parameters included an initial capital expenditure of USD 4 million, annual operational cost savings of USD 0.9 million, additional revenue of USD 0.35 million attributable to increased throughput, and annual maintenance expenses of USD 0.25 million. Within our methodological framework, the annual incremental cash flow was thus calculated according to equation (1).

Incorporating the reduced risk profile associated with improved data transparency – reflected in a 1.5% "digital premium" applied to the discount rate – the effective discount rate is adjusted to 10.5%. The five-year discounted cash flow analysis yields a net present value of NPV = -0.262 million USD, which would traditionally position the project at the borderline of financial feasibility. However, as argued in the previous sections, digital transformation projects should not be evaluated as static, standalone investments but rather as foundational digital infrastructures that create strategic flexibility for future expansion. In the context of PCS deployment, this strategic flexibility was manifested in the ability to integrate additional modules such as AIbased berth scheduling, blockchainenabled documentation flows, and automated congestion forecasting systems. Empirical evidence from comparable port systems suggested that these extensions may generate approximately USD 0.4 million in additional annual benefits, modifying the cash flow to:

$$CF_t^{ROV} = 1.0 + 0.4 = 1.4 \text{ mln USD}.$$

Applying the real options valuation logic to incorporate this "option to expand" significantly altered the project's financial profile. Under these revised conditions, the adjusted net present value became NPV_{ROV} = 1.233 mln USD, indicating a strongly positive investment outlook. This result empirically confirmed the non-linear nature of digital returns: performance gains raised not only from direct cost savings but also from cumulative ecosystem effects and the progressive expansion of digital functionality. The payback period further substantiated this conclusion. Given the rapid technological obsolescence typical of digital systems – estimated at 3-5 years – the payback period became a critical determinant of investment resilience. In the presented example, the adjusted payback period was:

$$PP = \frac{4}{1.4} \approx 2.9 \text{ years},$$

which falls well within the acceptable technological cycle. This accelerated recovery reflected the synergetic effects of increasing returns to scale: as more stakeholders adopt the digital platform, the marginal efficiency gains amplify, enabling internal reinvestment and reducing dependence on external financing. Overall, the empirical modelling results supported the core arguments advanced in this study. Digitalisation generated a multidimensional economic impact by simultaneously reducing costs, accelerating operational cycles, enhancing transparency, and creating strategic opportunities for innovation-driven growth. The proposed methodological framework made it possible to account for these complex and interdependent effects, thereby enabling more accurate and forward-looking investment decisions in the development of port infrastructure.

Comprehensive consideration of costs and digitalisation effects

A robust economic justification required a balanced view of the investment burden versus the efficiency gains. Within the proposed methodological approach, these factors were categorised into three interrelated components. The first component concerned investment expenditures (CAPEX) include not only tangible assets such as IoT sensors, 5G infrastructure, and servers, but also intangible elements, including digital platforms, data analytics systems, and cybersecurity protocols. The second component related to operational expenditures (OPEX) reflect a structural shift in cost composition, whereby labour costs decrease due to automation, reaching reductions of up to 60% in automated terminals, while costs related to system maintenance and data management increase moderately. Nevertheless, the overall effect remained positive due to the implementation of predictive maintenance and more efficient resource utilisation (Adabere *et al.*, 2021). The third component represented the digitalisation effect represents the core "value driver" within the methodology. It is manifested through several interconnected outcomes, including cost reduction, such as decreased energy consumption of approximately 17% and lower administrative overhead; operational acceleration, reflected in faster vessel turnaround and reduced cargo dwell time; and logistics synergy, achieved through enhanced real-time monitoring, which minimises "hidden costs" associated with delays and operational errors.

The proposed methodological approach explicitly incorporated the "security-through-efficiency" principle. By improving the accuracy of cash flow forecasting and ensuring real-time control over port operations, digitalisation acted as a tool for strengthening the financial and economic security of the port enterprise. However, the transition to a digital model introduced a new layer of volatility. The acceleration of financial flows and the reliance on automated systems necessitated a specialised framework for risk assessment. The strategic shift towards a digital-centric port model necessitated a redefinition of the port's economic resilience. While digitalisation mitigated traditional operational risks (such as human error or data opacity), it simultaneously introduced systemic cyber-vulnerabilities and the risk of technological lock-in. In this context, financial security was no longer just about liquidity and profitability; it was about the port's capacity to maintain core economic functions during potential system failures or cyber-attacks. Consequently, the proposed methodological approach treated digital investments not merely as profit-generating assets, but as critical infrastructure components that require a dual-layer protection strategy: one aimed at capital recovery and another at safeguarding the integrity of the digital ecosystem. This methodological foundation served as the basis for the subsequent analysis of cyber-risks, technological dependencies, and the broader financial security architecture required to protect port infrastructure in an increasingly digitalised global environment. This transition to risk-oriented evaluation was crucial for ensuring that the economic benefits identified in this section were not undermined by emerging digital threats.

Risk assessment and financial-economic security of port digitalisation

The transition to a digitalised port model shifted the paradigm of economic security from physical asset protection to the integrity and availability of data flows. In this context, financial and economic security was defined as the port's ability to maintain stable operations and capital recovery cycles despite internal and external digital disruptions. This approach was consistent with general principles of risk assessment in large-scale transport infrastructure projects, where uncertainty and long-term investment exposure require systematic identification and mitigation of risks (Tzvetkova, 2020). To develop effective mitigation strategies, the risks associated with port digitalisation were classified into three primary clusters. Technological risks include the potential for "technological lock-in", reflecting dependency on a single vendor, interoperability failures between legacy infrastructure and newly implemented digital platforms, and the rapid obsolescence of hardware, which may outpace the expected payback period. Financial risks were characterised by the volatility of maintenance costs, the possible underestimation of the total cost of ownership (TCO), and the risk of "stranded assets" in cases where a selected digital standard became unsupported within the global maritime environment. Cyber risks represented the most critical category in the context of smart ports and encompass threats such as data breaches, ransomware attacks targeting terminal operating systems (TOS), and GPS/AIS spoofing, all of which may lead to disruptions in port operations, physical congestion, and significant financial losses. Digital transformation acts as both a disruptor and a stabiliser of the port's risk environment. The proposed approach emphasised the "security-through-efficiency" mechanism, according to which improvements in operational performance directly contribute to risk reduction and overall system stability. Digitalisation reduced operational risks by automating manual processes and minimising the "human factor", which was responsible for a significant share of maritime accidents and documentation errors. The implementation of real-time IoT monitoring systems enabled early identification of potential equipment failures, reducing the probability of costly downtime and additional operating losses.

At the same time, digital transformation enhanced financial transparency using digital ledgers, including blockchain technologies, and integrated information platforms. These tools reduced the risks associated with corruption, shadow economic activities, and information asymmetry, thereby contributing to more stable and predictable cash flows. As a result, the financial position of the port was strengthened, which may improve its creditworthiness and reduce the cost of attracting external financing for future investment projects. To protect the investment-oriented development of water transport, a multi-level risk minimisation system was proposed, combining technological, organisational and financial measures. A key component of this system was the diversification of the digital architecture using open-source standards and modular cloud solutions, which reduced dependence on a single supplier and ensures the flexibility and scalability of digital systems. In parallel, the implementation of cyber resilience systems involved a transition from a passive protection model to an active resilience model, including regular stress testing of digital twins and the implementation of decentralised data storage protocols to increase the system's resilience to cyber threats.

At the economic level, this approach involved the formation of internal "digital reserve funds", as well as the use of specialised insurance instruments, such as cyber insurance, adapted to the specific risks of port logistics. Finally, constant adaptation of personnel remained a critical element of the system, since the changing risk landscape required support for the "man in the loop" principle. Ongoing training and development programs helped reduce the likelihood of internal security breaches and ensured effective management and oversight of increasingly automated systems. Thus, the assessment of risks and financial security was not a separate stage but an integral filter for the economic justification of investments. A project with a high IRR may be rejected if its "cyber-vulnerability score" exceeds the port's security threshold. This risk-adjusted evaluation ensured that digitalisation serves as a driver of sustainable and secure growth, rather than a source of systemic fragility in the maritime transport sector.

The proposed mechanism was based on the strategic conversion of operational advantages derived from digitalisation into multi-layered protective barriers for the port's financial and economic system. In this framework, digital transformation was viewed not merely as a tool for profit maximisation, but as the fundamental structural component of institutional resilience. By quantifying the impact of high-tech solutions on the stability of cash flows and the transparency of maritime operations, it was defined a clear transmission channel: from technological input to economic security output. This integration ensures that the "digital premium" acted as a buffer against market volatility and systemic disruptions. The structural relationship between specific digital effects and the resulting enhancements in the port's financial architecture was systematised in Table 2.

Table 2. Structural matrix of the digitalisation-security integration mechanism

Digitalisation effect	Impact on financial architecture	Security outcome (resilience benefit)
Real-time IoT data & Big Data analytics	Reduction of information asymmetry & operational opacity	Information security: mitigation of shadow economic activities and unauthorised data manipulation
Automation of cargo handling	Shift from variable to fixed costs; elimination of the "human factor"	Operational resilience: stabilisation of predictive cash flows and reduction in accident-related financial losses
Blockchain & smart contracts	Acceleration of transaction cycles and payment verifiability	Liquidity security: minimisation of accounts receivable risks and optimisation of working capital turnover
Predictive maintenance	Optimisation of the CAPEX/OPEX balance and asset life-cycle	Asset integrity: prevention of critical infrastructure failure and protection against "stranded asset" risks
Digital twins & AI simulation	Stress-testing of financial scenarios and risk modelling	Strategic security: data-driven justification of long-term investments and adaptive crisis management

Source: developed by the authors

The proposed mechanism of ensuring financial and economic security of port activities is based on a multi-level model that reflects the transformation of technological inputs into economic and security outcomes. The logic of the mechanism was grounded in the integration of digital technologies into port operations, which generate measurable financial effects and enhance the resilience of port systems under conditions of uncertainty. At the input level (technological impulse), the mechanism was driven by the implementation of advanced digital technologies, including the IoT, AI and 5G communication networks. These technologies enable the continuous generation and transmission of verified real-time data across port infrastructure. The availability of high-quality data significantly improved situational awareness and operational control, forming the basis for subsequent economic transformations.

At the transformation level (economic conversion), the generated data was converted into economic value through several key channels. First, increased transparency and data reliability contribute to the reduction of uncertainty, which allows for a lower discount rate in investment appraisal. This led to higher net present value of digital projects and improves their investment attractiveness. Next, the acceleration of operational processes, achieved through automation and real-time decision-making, reduced cargo handling time and shortened the payback period of investments. Also, the automation of routine operations and optimisation of resource allocation result in cost savings, which form an additional financial buffer, defined as a "liquidity cushion". This reserved enhances the financial stability of port operators and increases their ability to withstand external shocks.

At the security level (result), the cumulative economic effects of digitalisation lead to the formation of an integrated architecture of financial and economic security. This architecture provides protection against three main types of threats. Financial risks were mitigated through the stabilisation of cash flows, supported by predictable revenue streams and reduced operational costs. Operational risks were minimised due to the reduction of human errors and the increased reliability of automated systems. Investment risks were addressed through the application of flexible decision-making tools, including real options, which allowed for the adaptation of investment strategies to changing market conditions. The functioning of the proposed mechanism is illustrated in Figure 1.

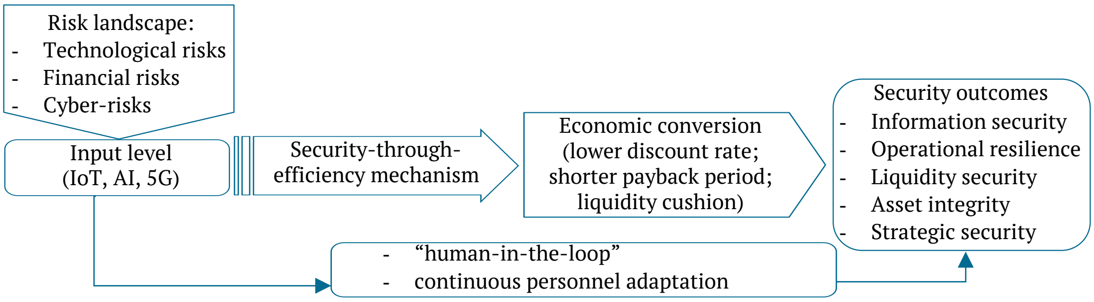

Figure 1. Mechanism of transformation of digital technologies into financial and economic security of port activities
Source: developed by the authors

The scientific significance of the proposed mechanism lay in the reinterpretation of the concept of financial and economic security in port activities. Unlike traditional approaches, which focused primarily on physical infrastructure protection and risk mitigation, the presented model considered data integrity and operational velocity as key strategic assets. This approach substantiated that the economic effects of digitalisation form not only an additional source of profitability but also a critical reserve that ensured the long-term sustainability of port systems in a volatile global environment. Thus, the mechanism demonstrated that digital transformation fundamentally changes the logic of investment evaluation and financial-economic security assessment in port infrastructure. The so-called "digital premium" should be interpreted not as an optional benefit, but as a necessary condition for maintaining competitiveness and ensuring financial and economic security in modern transport and logistics systems.

The obtained results confirmed that digital transformation in port activities generates a complex and multidimensional economic effect, which simultaneously affects cost structures, operational efficiency, and investment performance. Unlike prior studies that primarily focused on technological or organisational aspects, this research provided an integrated interpretation of digitalisation outcomes through financial and investment indicators. The empirical results demonstrating a 20-30% reduction in administrative and operational costs, as well as a decrease in vessel turnaround time and cargo dwell time, were consistent with existing findings. Similar cost reductions and efficiency gains were reported by World Bank (2025) and S. Adabere *et al.* (2021), who emphasised the role of digital platforms and automated data exchange in reducing transaction costs and operational delays.

At the same time, the present study extends these findings by quantifying their direct impact on cash flow generation and investment attractiveness, which is rarely addressed in previous research. The identified improvements in logistics efficiency and throughput capacity confirm the conclusions of M. Karlsson *et al.* (2023), who highlighted data availability and analytical capabilities as key drivers of performance in digitalised ports. However, while M. Karlsson *et al.* (2023) primarily analysed operational effects, this study demonstrated that these efficiency gains have a direct financial dimension, reflected in increased asset turnover and accelerated capital recovery. Thus, digitalisation should be interpreted not only as an operational improvement tool but also as a mechanism for enhancing investment efficiency. The results related to the optimisation of port charges and reduction of transaction costs align with the findings of the European Commission (n.d.), which emphasised the role of digital billing systems and integrated information platforms. In contrast to existing studies, the present research incorporated these effects into a broader financial model, showing that improved transparency and cost optimisation contribute to the formation of a "digital premium" through a reduction in the risk-adjusted discount rate.

The methodological contribution of this study was particularly evident in the development of an extended investment evaluation framework. The integration of dynamic capabilities and non-linear efficiency effects corresponded to the approach proposed by K.C. Shang *et al.* (2026), who demonstrated that digital maturity enhances organisational performance. However, this study advanced the discussion by applying these concepts at the infrastructure level and linking them to investment indicators such as NPV, *IRR*, and payback period. Similarly, the use of a multi-criteria perspective in evaluating port performance was consistent with V. Lorenčič *et al.* (2022), who underlined the importance of combining economic and operational indicators. Nevertheless, the present research expanded this approach by incorporating risk-adjusted financial metrics and by explicitly accounting for the effects of technological uncertainty and digital obsolescence. An important finding of this study was the identification of non-linear returns to digital investments, driven by ecosystem effects and increasing returns to scale, which was consistent with the business ecosystem perspective in port development (de Langen, 2023). This result supported the conclusions of Z. Su (2026), who highlighted the role of digital ecosystems in improving coordination among port stakeholders. At the same time, the current research extended this perspective by demonstrating how these ecosystem effects translate into shorter payback periods and self-financing investment cycles.

The results also confirmed the growing importance of resilience in digitalised port systems. In line with A.K.Y. Ng *et al*. (2025), digital technologies enhance adaptability and risk mitigation capabilities. However, this study contributed to the literature by proposing a structured classification of risks (technological, financial, and cyber) and by introducing a risk-adjusted investment filter, where financial indicators were evaluated in conjunction with cyber-vulnerability thresholds. Furthermore, the proposed "security-through-efficiency" mechanism provided a novel interpretation of financial and economic security in port activities. While previous studies (Ng *et al*., 2025) emphasised resilience, the present research demonstrated that operational efficiency itself became a source of financial stability by improving predictability of cash flows and reducing uncertainty.

The results highlighted that traditional investment evaluation approaches were insufficient for digital projects due to their shorter life cycles and higher uncertainty. The introduction of a technological lag coefficient and the application of Real Options Valuation addressed this limitation by aligning capital recovery with the dynamics of digital obsolescence. This finding complemented the existing literature on digital transformation and investment strategies (Mollaoglu & Gul, 2025), while providing a more detailed and operationalised methodological framework. Overall, the discussion confirmed that digital transformation fundamentally changes the economic logic of port development. The key contribution of this study lay in integrating operational, financial, and risk-related effects of digitalisation into a unified investment evaluation framework, thereby offering a more comprehensive basis for decision-making in the development of modern port infrastructure.

CONCLUSIONS

The conducted research demonstrated that the digital transformation of port operations, in the context of investment-driven development of water transport, was not merely a localised technological upgrade but represented a systemic structural evolution of the entire sector. The synthesis of empirical and analytical results confirmed that digitalisation generates substantial and quantifiable economic effects, including significant reductions in costs and operational time. Collectively, these outcomes significantly enhanced the overall investment attractiveness of port infrastructure assets. The main scientific contribution of the research lied in the development of an extended investment evaluation framework adapted to the specific characteristics of digital assets. This framework integrated financial performance indicators with risk-adjusted approaches and accounts for technological uncertainty, non-linear returns, and the shortened life cycle of digital solutions. In particular, the study introduced the concept of a "digital premium" associated with increased transparency, as well as a technological lag coefficient that aligned capital recovery with the dynamics of digital obsolescence.

Another key scientific contribution of the study was the conceptualisation of the "Security-through-Efficiency" mechanism, which demonstrated how digitalisation reinforces the financial and economic security of seaports by stabilising cash flows and transforming technological advantages into protective barriers within the financial architecture. At the same time, it was shown that high profitability indicators must be assessed through an integrated filter of digital-specific risks, including technological dependency and cyber threats. The proposed approach provided a comprehensive basis for more accurate and forward-looking investment decision-making in port development under conditions of increasing digitalisation and risk. Future research should focus on the development of quantitative metrics for assessing the cyber-vulnerability of digital projects and on investigating the role of artificial intelligence in ensuring the long-term resilience of Ukrainian port systems during post-war reconstruction and integration into the global digital ecosystem of maritime transport.

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Цифрова трансформація портової діяльності в контексті інвестиційно зумовленого розвитку водного транспорту

Анотація. Глобальний морський сектор перейшов від традиційної модернізації портів до системної цифрової інтеграції, що зумовило потребу в нових економічних підходах для обґрунтування інвестицій у смарт-технології із одночасним забезпеченням фінансової безпеки. Метою дослідження було обґрунтування методологічних засад цифрової трансформації портової діяльності в контексті інвестиційно зумовленого розвитку водного транспорту. У дослідженні застосовано комплексний методологічний підхід, що охоплює системний аналіз, порівняльний і структурний аналіз, а також економіко-статистичне моделювання для оцінювання інвестиційної ефективності за показниками грошових потоків, прибутковості та оцінювання ризиків. Отримані результати засвідчили, що цифровізація функціонувала як багатовимірний економічний драйвер, знижуючи адміністративні та документаційні витрати на 20-30 %, час оброблення суден у порту – до 25 %, а час перебування вантажів – приблизно на 40 %. У дослідженні запропоновано удосконалену методику оцінювання інвестицій, яка інтегрує оцінювання реальних опціонів для врахування стратегічної гнучкості, а також введено цифрову премію, що коригує ставку дисконтування на основі підвищення операційної прозорості. Ключовою інновацією стало включення коефіцієнта технологічного відставання до розрахунків строку окупності, що узгоджує відновлення капіталу з коротшим циклом цифрового застарівання. Результати засвідчили, що цифрові інвестиції генерують нелінійну віддачу через зростаючу віддачу від масштабу в міру приєднання більшої кількості стейкхолдерів до екосистеми, забезпечуючи коротші строки окупності та цикли самофінансування. Крім того, у дослідженні концептуалізовано механізм інтеграції ефектів цифровізації в архітектуру фінансової безпеки порту, доведено, що технологічна прозорість і операційна швидкість виступають критичними резервами інституційної стійкості. Класифікація цифрових ризиків на технологічний, фінансовий і кібернетичний кластери дала змогу здійснювати ризик-орієнтоване оцінювання, за якого інвестиційні проєкти фільтруються через поріг безпеки для запобігання системній вразливості. Практична цінність роботи полягає в розроблених інструментах економічного обґрунтування проєктів смарт-портів, які дають змогу портовим операторам та інвесторам точно моделювати інкрементальні ефекти, оптимізувати структуру капіталу та зміцнювати фінансову безпеку інфраструктури водного транспорту в цифровізованому глобальному середовищі

Ключові слова: транспортно-логістичні системи; розвиток портової інфраструктури; інвестиційна ефективність; операційні витрати; управління грошовими потоками; оцінювання ризиків; фінансово-економічна безпека