Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 129 **2025**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2025.129.9

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Melnyk, O., Onyshchenko, S., Zhykharieva, V., Pavlova, N., Volianska, Y., Andriievska, V., Korobkova, O. Analytical model for ship grace-period optimization via a single window platform: a Tianjin port case study. *Scientific Journal of Silesian University of Technology. Series Transport*. 2025, **129**, 147-168. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2025.129.9

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ANALYTICAL MODEL FOR SHIP GRACE-PERIOD OPTIMIZATION VIA A SINGLE WINDOW PLATFORM: A TIANJIN PORT CASE STUDY

Summary. The article presents an analytical model for optimizing the "grace period" of mooring and documentary clearance of ships in the port of Tianjin by

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introducing a centralized "single window" platform. The functional roles of the key documents - Forwarder's Cargo Receipt (FCR) and Shipping Order - regulating the readiness of cargo for loading and confirming the completion of customs clearance are investigated. Based on regulatory analysis, expert interviews, and simulation modeling, critical bottlenecks in the processes of verification and berth slot assignment are identified. A stochastic model of the total processing time was developed, where each stage is described as an independent, normally distributed random variable. Using this model, the probability of exceeding the permissible processing interval is estimated, and the feasibility of automating document flow is substantiated. Technical and organizational solutions for implementing a unified digital infrastructure, including standardized exchange formats, double data validation, electronic stamping, and integration with PCS/TOS, are proposed. This creates the basis for utilizing these results in the development of intelligent port systems and enhancing the efficiency of logistics operations.

Keywords: port operations, project optimization, maritime logistics, berth assignment, management system, shipping, documentation flow, freight forwarding, cargo handling, shipping order, customs clearance, transportation process, port community systems, stochastic process simulation, terminal operating systems, operational efficiency, stakeholder coordination

1. INTRODUCTION

The Port of Tianjin is one of the largest transshipment hubs in Northern China, with millions of tons of cargo passing through it annually. Ensuring timely delivery and mooring of vessels in the port depends on the clarity of documentary procedures and operational interaction between shippers, freight forwarders, customs, terminals and ship agents. Particularly important are the FCR (Forwarders Certificate of Receipt) and Shipping Order documents, which determine the readiness of the cargo for loading and the port's ability to assign a berth to the vessel. In today's environment of growing security boundaries, digitalization of the supply chain, and increased customer expectations, improving these procedures is key to increasing the efficiency and reliability of port operations.

The modern scientific literature addresses the issues of digitalization and optimization of port operations in several interrelated areas. Thus, the digital transformation in maritime logistics is studied in the work of Zeng et al. (2025), who conducted a systematic review of the drivers and obstacles to digitalization in maritime logistics, finding that there is a lack of common data exchange standards and an adequate level of digital literacy among employees. Fruth & Teuteberg (2017) emphasize the gaps in the integration of information systems between chain actors, while Jović et al. (2024) use the example of Croatia to demonstrate how digital transformation increases process transparency and reduces cargo handling time.

Blockchain and secure document exchange have been studied by Liu (2021) and Alahmadi et al. (2022) comparing blockchain-based platforms for the exchange of cargo documents, proving the benefits of a distributed ledger in reducing the risk of forgery. Chang et al. (2019), Jovanović et al. (2022), Yang (2019), and Guan et al. (2024) summarize the possibilities of blockchain in global supply chains, while Ni & Irannezhad (2023), Shin et al. (2023), and Karakaş et al. (2021) emphasize its role in port ecosystem management.

Information systems and terminal automation are presented by González-Cancelas et al. (2020) and Camarero Orive et al. (2020) who apply SWOT analysis to assess the digitalization and automation of container terminals in Spain. Heilig & Voß (2017) categorize information systems in ports, and Lee et al. (2018) propose a DSS for making ship speed decisions based on large amounts of weather data.

Decision support and simulation in Lee et al. (2018), where the authors developed a decision support system for optimizing ship speed using archived meteorological data, and Wang et al. (2024) simulate the traffic of ultra-large ships in the port of Ningbo Zhoushan, providing important insights for berth slot management.

Prediction of cargo flows and downtime has been studied by Patil & Sahu (2016), Al-Deek (2001) and Munim et al. (2023) where they compare regression, time series, and hybrid models to forecast container flows in key Asian ports. Yu et al. (2025) combine graph theory and time series for a detailed traffic forecast, while Morales-Ramírez et al. (2025) use autoregressive models to analyze national freight traffic. Chu et al. (2025) and Pham & Nguyen (2025) apply ensemble approaches and machine learning to ship arrival time forecasting, and Huang et al. (2024) apply them to terminal energy requirements. Das & Saxena (2025), Osadume et al. (2025), Abd Rahim et al. (2024), Nwoloziri et al. (2025), and Cuong et al. (2022) study the impact of the COVID-19 crisis on cargo flows, downtime costs, and port recovery.

The economic impact of the crisis is assessed in Das & Saxena (2025), which analyzes the impact of the pandemic on freight and revenues in India, Osadume et al. (2025) on the operation of Nigerian ports, and Nwoloziri et al. (2025) on the costs of delays in Apapa ports. Models of risk and safety of ship operations were analyzed by Guo et al. (2024) developed an optimal emergency resource allocation model with multi-criteria optimization, and Darwich & Bakonyi (2025) investigated the development of port infrastructure in East Africa. Gondia et al. (2023) apply ML methods for dynamic risk assessment in construction, Nagurney et al. (2024) - integrated insurance for operations during military conflicts. Melnyk et al. (2024, 2025) serially develop concepts for the safety of cargo operations, analysis of the structural reliability of navigation systems, and cluster analysis of incidents. Kobets et al. (2023), Zinchenko et al. (2023, 2024) propose automated algorithms for positioning, collision avoidance, and parametric rolling, while Melnyk et al. (2023) evaluate the effectiveness of expert risk management methods.

Specialized studies of port management have been carried out by Abd Rahim et al. (2024), who studied the impact of air pollution on the health of workers in the Klang port area. Guo et al. (2025) forecasted water needs for irrigation of oil ports, Luidmyla et al. (2025) proposed a new approach to modeling the unloading process, Varbanets et al. (2024) – who designed diagnostics of diesel engines of marine vessels; Zhikharieva (2025) – benchmarking of intangible assets of shipping, and Nikolaieva et al. (2025) formalized hybrid models of terminal management based on KPIs.

Despite a wide range of studies on the digitalization of port processes, blockchain solutions, and information systems in terminals, the integration of key FCR and Shipping Order documents into a single electronic window remains underestimated in current practice. The absence of such a solution in ports can lead to significant delays at the stages of customs clearance and mooring assignment for ships.

Problem statement. Despite the important role of the FCR as the primary confirmation of cargo acceptance by the forwarding agent, this document does not certify the fact of customs clearance and readiness of the cargo for loading onto the vessel. At Tianjin port terminals, the FCR alone does not provide a basis for mooring slot assignment: without a stamped Shipping Order, the port cannot verify that the cargo has cleared all customs formalities and is located in the proper place in the terminal.

Consequently, freight forwarders and shipowners encounter delays in the mooring process, extending the “grace period” and resulting in additional financial costs. The lack of an integrated data exchange system between freight forwarders, customs, the port authority, and ship agents causes bottlenecks that have a negative impact on port throughput and reduce the overall efficiency of the supply chain.

Purpose and objectives of the study. The purpose of this study is to analyze the existing workflow and procedures of port operations in Tianjin, identify bottlenecks related to the use of FCR and Shipping Order, and propose practical digital solutions to improve them.

Objectives:
- describe the regulatory framework and the role of the FCR and Shipping Order in the port of Tianjin;
- identify the key points of delay in the customs clearance procedure and ship mooring assignment;
- analyze the experience of terminals in checking the status of cargo in the port's internal systems;
- develop recommendations for implementing a single electronic window and automating document exchange;
- estimate the expected economic effect of reducing downtime and optimizing the grace period.

The scientific novelty of the article lies in the combination of probabilistic modeling of the total vessel downtime (with the distribution of the constituent stages of the document flow: FCR, customs clearance, verification, slot assignment) with the economic function of downtime costs and the concept of implementing a "single electronic window" for the automated exchange of FCR and Shipping Order. For the first time, an analytical model of exceeding the "grace period". Based on real data from the Tianjin Port, it is proved that digital integration of document flow can provide annual savings and increase port throughput.

2. METHODOLOGY

This study uses a combined approach that combines qualitative and quantitative methods to comprehensively examine the document flow process at the Port of Tianjin. First, a detailed analysis of the regulatory framework was conducted: official instructions of the Administration of Customs of the People's Republic of China and the Tianjin Terminal Rules were studied, and a comparative analysis of the internal procedure cards Forwarders Certificate of Receipt (FCR) and Shipping Order was performed. It is important that one of the authors has more than many years of experience in Chinese ports, including the port of Tianjin as a representative of an international shipping company, which also allowed the authors to take into account the practical nuances and internal logistics of port procedures and to reproduce the formal requirements for the content and sequence of these two key documents.

Secondly, semi-structured interviews with port industry practitioners were organized to identify the actual processing times and reasons for delays: interviews were conducted with three ship agents, two representatives of forwarding companies, and a terminal operator. The interviews provided empirical data on the time intervals between the issuance of the FCR, the customs stamping of the Shipping Order, and the mooring slot assignment.

And thirdly, to assess the existing IT infrastructure of the port, a review of the Shipping Order acceptance module in the Port Community System (PCS) was carried out. The user interface, business logic of document processing, and data exchange mechanisms between PCS, the customs system, and ship agents were analyzed.

Finally, in the quantitative part of the study, a statistical analysis of ship calls during 2022-25 was performed. Based on the collected data, the average time from the issuance of the FCR to the affixing of the Shipping Order customs stamp, as well as the time until the actual mooring slot is assigned, was estimated. The obtained numerical characteristics formed the basis for further development of the analytical model and assessment of economic losses due to delays.

3. RESULTS

The regulatory framework and the role of FCR and Shipping Order in the port of Tianjin

Before moving on to describe specific procedures, it is important to outline the legal framework in which the document flow in the port of Tianjin operates. A combination of national laws, municipal regulations, and international guidelines forms a two-stage cargo verification mechanism: first, the freight forwarder confirms the fact of acceptance, and then the customs and terminal confirm the cargo's readiness for operations.

The regulation of document flow in the port of Tianjin is based on both general Chinese legislation and special rules of the port administration and customs authorities. Key regulatory sources include:

1. The Law of the People's Republic of China "On Customs Control" and bylaws that establish requirements for the execution of cargo documents, the procedure for their submission to the customs authorities, and the procedure for affixing customs stamps. These provisions stipulate that only a document with a customs stamp (Shipping Order) is recognized as an official confirmation of the completion of the customs clearance procedures and the readiness of the cargo for unloading or loading onto a vessel.
2. The Tianjin Port Administration Rules approved by the Tianjin Municipal Port Administration, which regulate the procedures for mooring assignment, berth management, and interaction between the port authorities, terminals, ship agents, and freight forwarders. According to these rules, terminals are obliged to check the availability of a Shipping Order before issuing berthing instructions.
3. The harmonized rules of the International Federation of Freight Forwarders (FIATA) on Forwarders Certificate of Receipt (FCR), which globally recognize the FCR as an internal document of the forwarder to confirm the acceptance of cargo. However, in China, the FCR, although compliant with the FIATA international standard, is used primarily to register the fact of acceptance of cargo from the sender but is not a basis for customs clearance or mooring assignment (Table 1).

Tab. 1

Key regulatory sources and their requirements

Regulatory source	Main provisions
Customs Law of People's Republic of China	- requirements for cargo documents; - the customs stamp on the Shipping Order is the only proof of customs clearance and readiness for loading.
Tianjin Port Administration Rules	- list of documents for mooring assignment;

	- mandatory check of the Shipping Order before issuing mooring instructions.
FIATA recommendations on FCR	- FCR is recognized as an international standard for confirming the acceptance of cargo by the forwarder; - in China, the FCR does not replace the Shipping Order during processing at the port.

Study of the role of both documents in the process

The Forwarder's Certificate of Receipt (FCR) is a key document that serves as an internal confirmation of cargo acceptance by the forwarder. Its main role is to record the fact of cargo transfer, accompanied by a detailed description: the name of the sender, the number of pieces, the nature of the cargo, the port of destination, and other mandatory details. All this data must fully comply with the future Shipping Order submitted to the customs authorities.

In practice, the FCR serves as the basis for the formation of the Shipping Order: the freight forwarder uses the information from the FCR to prepare a draft document, which is then sent for approval and stamping by the customs. Thus, the FCR performs not only a confirmatory but also a translational function in the customs clearance procedure, reflecting internal control at the stage of cargo acceptance.

Table 2 shows the main tasks performed by FCR in the process of organizing port logistics.

Tab. 2

Main tasks performed by FCR

Function	Description
Confirmation of cargo acceptance	The name of the sender, description, quantity, and port of destination are the same details as in the Shipping Order
The basis for the formation of the Shipping Order	Based on the FCR data, the forwarder initiates customs clearance and automatically transfers these details to the Shipping Order project

The role of Shipping Order in the port procedures

Shipping Order is a central document in the system of port clearance and interaction between participants in the logistics process. Its functional importance is as follows:

- confirmation of customs clearance: the customs stamp on the Shipping Order certifies that the cargo has been officially cleared and allowed for loading or unloading. This is the only document that has legal force in confirming the completion of all customs formalities;
- basis for planning port operations: in the port of Tianjin, the Shipping Order is a mandatory document for setting the time and place for mooring a vessel. Terminal operators use it to reserve a mooring slot, which helps to avoid delays and optimize cargo turnover;
- communication interface: through integration with the Port Community System (PCS), the Shipping Order is automatically sent to customs, port authorities, ship's agent and other responsible services. This ensures the coordinated work of all parties – from the moment the cargo arrives to the moment the vessel is actually moored.

Thus, the Shipping Order not only formalizes the fact of customs clearance and serves as a logistics coordinator and a digital marker of cargo readiness for processing. Its functions are systematized in Table 3.

Tab. 3

Main functions and designation of Shipping Order

Function	Description
Proof of customs clearance	The electronic or paper stamp of the customs office on the Shipping Order confirms that the cargo has passed all the formalities
Reasons for mooring arrangements	Only after successful verification of the Shipping Order, the terminal operator reserves a berth slot and schedules maintenance
Communication bridge via PCS	The Shipping Order is sent out automatically through the Port Community System, informing customs, the terminal and the ship's agent about the readiness of the cargo

Upon analyzing the regulatory framework and the respective roles of the two documents, it becomes clear that, while the FCR is responsible for the initial confirmation of acceptance, it cannot form the basis for any port operations without a customs clearance stamp. Conversely, the Shipping Order bearing a customs stamp carries legal force for transporters and is a technical necessity for port services. This two-step process strikes a balance between the speed of document processing and strict compliance with Chinese customs and legal requirements.

Thus, the combination of international FIATA (FCR) recommendations and Chinese national requirements for the Shipping Order creates a two-stage cargo control mechanism: the first stage confirms acceptance, and the second stage ensures readiness for operations in the port. This strikes a balance between the efficiency of document flow and compliance with Chinese customs and legal requirements.

Key points of delay in the customs clearance procedure and the mooring assignment

The main bottlenecks in the procedure of paperwork and processing of documents that lead to delays in ship calls at the Port of Tianjin can be grouped as follows:

1. Reconciliation and verification of details between the FCR and the draft Shipping Order often require additional time: if the data on the port of destination, cargo name, or shipper does not match, the forwarder has to correct errors and resubmit the application through the Port Community System, which adds an average of 1-2 hours of downtime.
2. Waiting for the customs stamp is the longest stage: the customs officer checks not only the documents but also the physical condition of the cargo, if necessary, and then affixes the stamp. At peak times, this procedure takes an average of 4-6 hours and can extend up to 8 hours.
3. Technical failures in the exchange of XML-packages between the customs and port systems are likely to lead to "hangs" or format errors (duplicate files, incorrect encoding), which makes information about the stamped Shipping Order unavailable to the terminal for an additional 1-2 hours.
4. Upon receipt at PCS, the Shipping Order must be manually verified by the berth department operator: all cargo data must be checked against the terminal's internal database (including the location of containers), which usually takes another 1-2 hours.

Finally, only after successful verification of the Shipping Order, the port administration generates a berth slot (lineup instruction). During normal business hours, this process takes up to 1 hour, while during night shifts and weekends it can take up to 3 hours. Taken together, all these stages form a total "grace period" of 8-12 hours, which often exceeds the regulatory limits and causes significant financial losses due to the ship's idle condition (Figure 1).

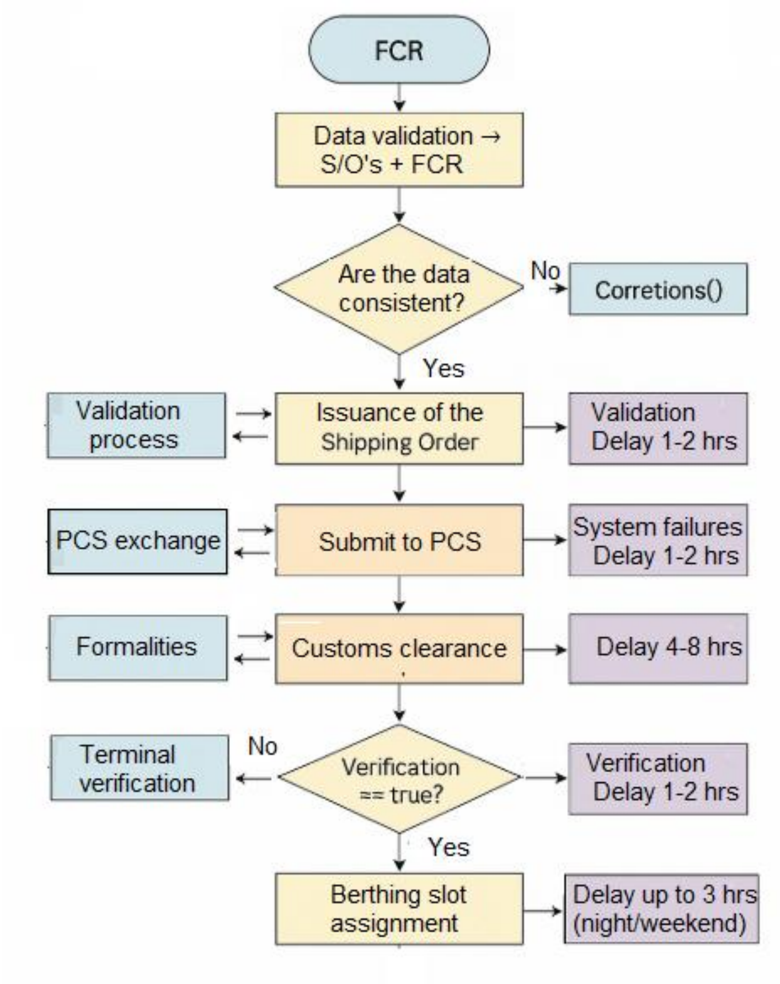

Fig. 1. Document processing algorithm and berth slot assignment

The diagram in Figure 2 shows the step-by-step process of Shipping Order issuance and berth slot assignment, with key points of delay at each stage highlighted. Each block indicates the main action and sequence of operations, and below them are possible delays (hours) with the corresponding warning icons.

The diagram shows that the largest downtime is during customs clearance (4-8 hours) and initial data verification (1-2 hours for each of several steps). Smaller delays (1-2 hours) are caused by system checks and data exchange in PCS, and during non-operational hours, an additional 1-3 hours when assigning a berth slot. These bottlenecks should be optimized by automating validation, increasing the throughput of exchange systems, and introducing flexible slots to accommodate night and weekend shifts.

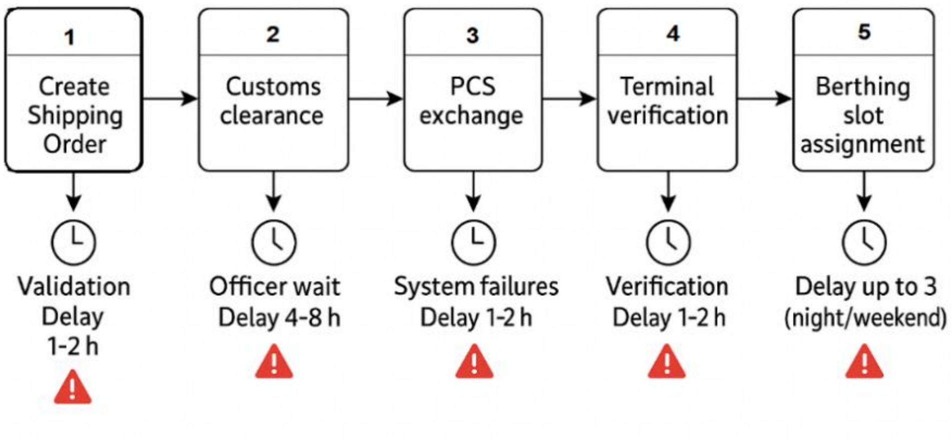

Fig. 2. Shipping Order processing process with key points of delay

As a result, it takes an average of 8-12 hours from the general moment of issuing the FCR to receiving the mooring instruction; on peak days, this interval can reach 14-16 hours, which significantly exceeds the optimal "grace period" and leads to additional costs due to vessel downtime.

Additionally, a stochastic modeling of the total delay of the procedure "FCR - SO - PCS - customs clearance - mooring" was carried out. The Monte Carlo method with 10,000 iterations was used, in which delays at each of the five stages were generated according to uniform distributions (1-2 hours, 4-6 hours, 1-2 hours, 1-2 hours, 1-3 hours, respectively). The resulting distribution of total time allows us to estimate the key statistical characteristics of the process and the probability of exceeding critical time thresholds, Figure 3.

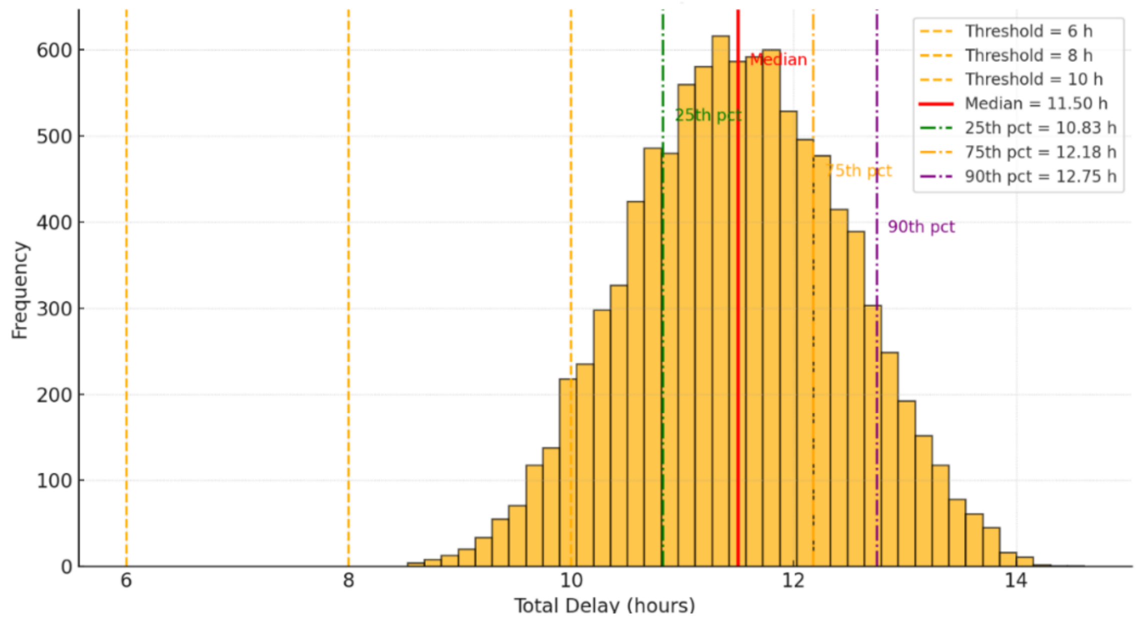

Fig. 3. Distribution of the total process delay (histogram) with thresholds of 6 hours, 8 hours, 10 hours, as well as the median (50%), 25%, 75%, and 90% quantiles

The range of results clearly shows that the median total delay is approximately 11.5 hours, the 25th percentile is 10.8 hours, the 75th percentile is 12.2 hours, and the 90th percentile is 12.8 hours. Thus, the probability of exceeding the 10-hour limit reaches about 94%, which indicates a high risk of delays beyond this threshold. The less critical thresholds of 6 and 8 hours are almost always exceeded (with a probability of approximately 100%), which requires optimization of key process steps to reduce downtime and increase the efficiency of the supply chain.

Experience of terminals in checking cargo status in the port information system

After the Shipping Order is created and stamped by customs, an email is instantly generated in PCS and sent to the corresponding Terminal Operating System (TOS) module of the terminal. In TOS, the cargo receives the "Cleared" status, which makes it available for further mooring planning. The terminal operator views the Shipping Order data, the actual location of the container through the WMS, and additional parameters (weight, radiological checks) in a single interface. If any field does not match, the system displays a "yellow" warning status and blocks automatic slot generation.

Once the Shipping Order is in the "Cleared" status, the TOS automatically sends SMS and e-mail notifications to the ship's agent and freight forwarder. Although the formal SLA for status confirmation is 30 minutes, during peak periods this step takes about 45-60 minutes. For exceptional situations when the application hangs due to XML errors or API timeouts (1-2% of cases), operators use the manual tool "Force Clear" after visually checking the original document.

Every day, TOS generates a report on key metrics: the average time from "Cleared" to the issuance of a berthing instruction (≈ 1 hour) and the share of Shipping Orders with delays of more than 2 hours (less than 3% of cases). These indicators are analyzed weekly by the port's customer service to identify trends and eliminate bottlenecks.

In Figure 4 shown a generalized sequence-diagram, illustrating the main data flow between the forwarding agent, Port Community System (PCS), Customs, and Terminal Operating System (TOS).

The diagram illustrates the sequence of digital processing in the Port Community System (PCS), where the agent sends the FCR and Shipping Order, the PCS requests electronic approval from customs, and then receives back the confirmed document with a stamp. PCS then informs the TOS system that the cargo is ready, and TOS, in turn, sends instructions for mooring the vessel.

Field interviews and a detailed review of internal procedures revealed that each terminal at the Port of Tianjin uses its own Terminal Operating System (TOS) module, integrated with the port-wide Port Community System (PCS). This combination allows for near-instant data exchange and automation of key steps, but also reveals technical bottlenecks that need to be addressed when optimizing processes, Table 4.

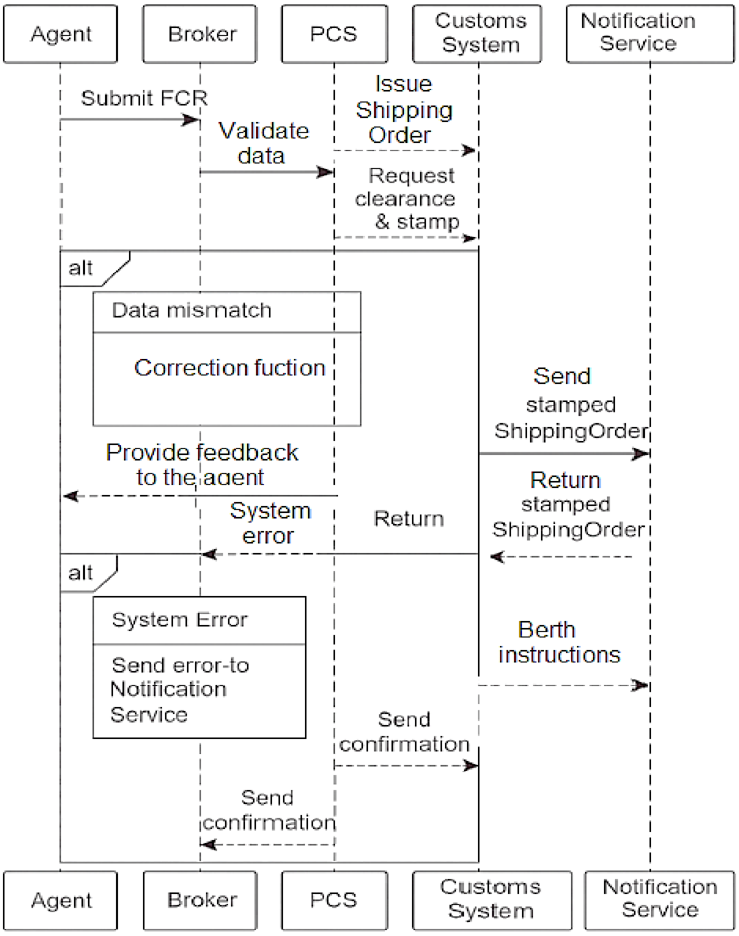

Fig. 4. FCR and Shipping Order processing in the Port Community System (PCS)

Tab. 4

Main stages and mechanisms for checking the status of cargo in PCS & TOS

№	Stage / Functional unit	Description of the operation and key indicators
1	PCS - TOS integration	- after the Shipping Order is stamped in PCS, a notification is automatically sent to the terminal's TOS; - the "Cleared" status means that the cargo and the vessel are ready for mooring.
2	Multimodal verification	- the TOS interface contains Shipping Order data, container location (WMS), and the results of additional checks; - a "yellow" warning status in case of discrepancies blocks further processing.

3	Automated notifications and SLAs	- SMS/email notification to the agent and forwarder when the status is "Cleared"; - the target SLA is 30 minutes; in fact, 45-60 minutes during peak hours.
4	Handling of exceptional situations	- 1-2% of applications hang due to XML errors/API timeouts; - Force Clear tool for emergency status assignment after visual inspection.
5	Analytics and reporting	- daily report: time from "Cleared" to "Berth Instruction" (≈ 1 hour), share of delays > 2 hours (< 3%); - weekly trend analysis by the customer service to identify and eliminate bottlenecks.

Thus, the deep integration of PCS with TOS allows terminals to quickly confirm the readiness of cargo, minimize human errors, and reduce delays. At the same time, the Force Clear mechanism and daily monitoring of key indicators ensure the stability of the process even in the event of technical failures.

Recommendations for the implementation of a single electronic window and automated document exchange

To improve the document flow process, in this case using the example of the port of Tianjin, several interrelated measures were introduced aimed at eliminating critical bottlenecks related to the use of FCR and Shipping Order. These measures address the technological, procedural, and organizational aspects of creating a digital environment designed to reduce processing time, increase transparency, and minimize human involvement in operations.

The first step is to create a centralized Single Window platform that will bring together all the key parties in the chain - freight forwarders, customs, terminal operators and ship agents - in a single digital system. This will simplify the submission of documents and reduce the number of duplications. At the same time, standardized data formats (XML/JSON) that comply with international protocols should be introduced using a secure transmission channel.

An important step is the automatic creation of Shipping Orders based on FCRs, which reduces the time for verification and minimizes errors. Customs electronic stamping is integrated into the same digital space, providing a transparent and consistent approval procedure. The system must support automatic notifications and SLA compliance monitoring, which allows for avoiding delays and responding promptly to deviations. It is also planned to implement double data validation, both hard and soft, with prompts for correcting errors before submission.

Ultimately, all transactions should be documented in a secure distributed ledger to guarantee audit transparency. The implementation occurs gradually, accompanied by compulsory staff training. The overall framework of these steps is outlined in the table below, Table 5.

Each of the above measures is aimed at improving a specific node of interaction between the participants in the supply chain. For example, a centralized platform provides a single sign-on, while automatic document generation and double validation improve accuracy. The combination of electronic stamping with blockchain allows for complete transparency and immutability of documentary traces, which is especially important for customs and legal control. And the phased implementation with training guarantees smooth adaptation of the system without disruptions in real port traffic.

Tab. 5

Key measures for implementing electronic document exchange in the port of Tianjin

№	Component	Description	Functional role
1	Centralized platform "Single Window"	A single web interface for all participants to interact: FCR, customs, TOS, agents	Unification of processes, reduction of duplication, centralized access
2	Standardization of formats (XML/JSON) and API	Use of templates, RESTful API with TLS and OAuth 2.0	Seamless integration of systems, data protection
3	Automatic creation of Shipping Order	Automatic copying of data from FCR to SO	Reducing errors, speeding up document preparation
4	Integrated electronic customs stamping	Electronic stamping by customs in the "Single Window"	Refusal from papers, instant status transfer
5	Automatic notifications and SLA control	SMS/email notifications, timers to meet deadlines	Ensuring efficiency, preventive management
6	Double data validation	"Hard" - blocks, "soft" - prompts	Improving data reliability, reducing the number of errors
7	Distributed transaction log	Blockchain or DLT to record all actions	Transparency, secure change history, audit
8	Gradual implementation and training	Pilot stages, trainings, feedback collection	Minimizing implementation risks, user adaptation

As a result of the analysis of current bottlenecks in the FCR and Shipping Order exchange procedure in the Port of Tianjin and the formulation of a number of recommendations aimed at creating a single digital space for all chain participants, a structure based on the principles of interoperability, security and increased efficiency of document processing is presented in Figure 5.

The implementation of these recommendations will allow particularly the Port of Tianjin to provide a fully digital, transparent, and controlled document flow - from the moment the cargo is received by the forwarder to the actual mooring of the vessel-reducing delays and downtime to a minimum.

Estimation of the expected economic effect

The analysis shows that the average vessel demurrage rate at the Tianjin port is about 500 USD/hour. In the current environment, due to delays in Shipping Order verification, the "grace period" increases to 14-16 hours, while after the introduction of a single electronic window and automation of document flow, the expected delay will be reduced to 4-6 hours. Based on the difference of 9 hours (14-5), the savings in downtime per ship call will be approximately USD 4,500. At 120 calls per year, this translates into direct savings of about USD 540,000 in downtime tariffs alone.

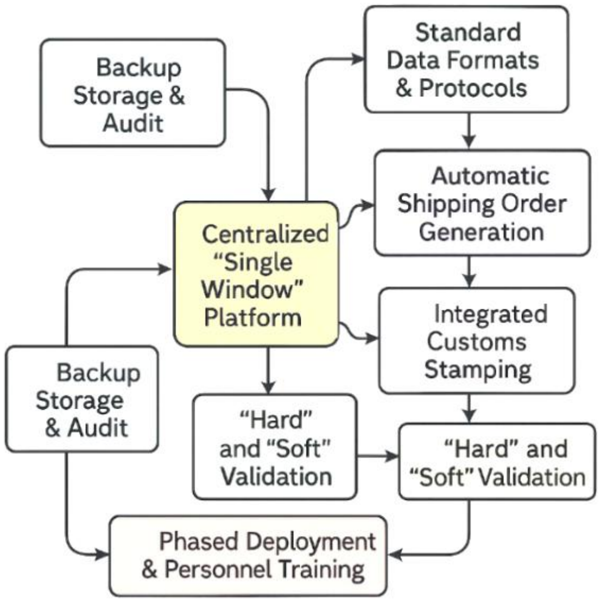

Fig. 5. Implementation roadmap for a centralized single-window and automated document-exchange system

In addition, reducing the 'grace period' increases the port's overall throughput by 5-7%, equivalent to servicing an extra 6-8 vessels per month. At an average freight rate of USD 50,000 per vessel, calculated annually, this equates to an additional revenue of USD 3-4 million. Therefore, the total economic impact of optimizing document flow, including direct savings on downtime and revenue generated by increased traffic, can exceed USD 4 million per year.

In order to quantify the impact of procedural delays on the total vessel downtime in the port of Tianjin and monitor the risk of exceeding the "grace period," it is advisable to build an analytical model that takes into account the individual components of the document flow. Each of these stages - issuance of the FCR, customs clearance and stamping of the Shipping Order, verification of documents in the port system, and berth slot assignment - has its own average execution time and its own variance. By combining them into an aggregate random variable, we can estimate not only the expected downtime, but also the probability of a critical exceedance of the permissible interval.

For an analytical description of the logistics process of vessel registration and berthing, let us denote the main stages that constitute the total processing time:

- T_{FCR} - time from cargo reception to issuance of the Forwarder's Cargo Receipt (FCR);
- T_{clear} - time required for customs clearance and stamping of the Shipping Order;
- T_{ver} - time for document verification in PCS/TOS systems (Port Community System / Terminal Operating System);
- T_{slot} - time spent waiting for and being assigned a berth slot.

The total vessel idle time associated with the port entry process is then modeled as the sum of these components:

$$T_{\text{total}} = T_{\text{FCR}} + T_{\text{clear}} + T_{\text{ver}} + T_{\text{slot}} . \quad (1)$$

This equation provides a structural decomposition of the turnaround time and serves as the basis for probabilistic modeling.

To incorporate variability and uncertainty inherent to port operations, we treat each component T_i as a random variable. Specifically, we assume that:

- each T_i follows a normal distribution with mean μ_i and variance $\sigma^2{}_i$;
- variables are mutually independent, since they reflect distinct administrative or logistical phases.

Formally:

$$T_i \sim \mathrm{N}\,(\mu_i, \sigma_i^2), \quad i \in \{\mathrm{FCR}, \mathrm{clear}, \mathrm{ver}, \mathrm{slot}\}. \tag{2}$$

Due to the additivity and independence of normally distributed variables, the total processing time T_{total} is also normally distributed, with the following parameters:

$$T_{\text{total}} \sim \mathrm{N}\left(\sum_i \mu_i, \sum_i \sigma_i^2\right), \tag{3}$$

where: μ_i - expected duration of stage i, $\sigma^2{}_i$ - variance of stage i.

This probabilistic model enables us to quantify both the expected delay and the dispersion around the mean, which are critical for reliability assessment.

Ports often define a grace period threshold, denoted T^*, representing the maximum allowable time for documentation and berthing before penalties or surcharges apply.

We aim to estimate the probability that the total time exceeds this threshold:

$$P(T_{\text{total}} > T^*) = 1 - \Phi\left(\frac{T^* - \sum_i \mu_i}{\sqrt{\sum_i \sigma_i^2}}\right), \tag{4}$$

where $\Phi(\cdot)$ - cumulative distribution function (CDF) of the standard normal distribution.

This expression quantifies the risk of process overrun, which can be used by port authorities and operators to set buffer times, prioritize automation, or revise scheduling policies.

Beyond operational risks, excessive turnaround time directly translates into monetary losses due to vessel idle charges. Let c_{rate} denote the per-hour cost of vessel idle time (e.g., USD/hour). Then, the expected financial loss due to delays is modeled as follows:

$$C = c_{\text{rate}} \cdot \mathrm{E}\left[\max\left\{0, T_{\text{total}} - T^*\right\}\right]. \tag{5}$$

This formulation represents the expected value of the positive deviation of total processing time above the grace period, multiplied by the unit cost of delay. It corresponds to the area under the tail of the distribution beyond T^*, weighted by cost.

Since $T_{total} \sim N(\mu_{sum}, \sigma^2_{sum})$, the above expectation can be numerically evaluated or approximated using known results for truncated normal distributions.

Given empirical estimates μ_i and σ_i from observed data (e.g., from port operations logs), this model enables the computation of:
- expected processing time;
- probability of exceeding the grace period;
- expected economic loss due to idle time.

These results can be represented as simulation outputs to compare scenarios with and without automation, assess the impact of parameter changes, or identify bottlenecks.

Thus, this model can be used not only to calculate the average downtime and determine the probability of exceeding the optimal "grace period". It also helps to estimate economic losses and obtain an estimate of the direct financial costs of downtime tariffs. In practice, by substituting the empirically determined μ_i and σ_i, we get the estimated cost of delays and can compare it with the expected savings from the introduction of an electronic window and automation of document exchange.

To illustrate how the individual stages of the document flow procedure affect the total vessel downtime, a stack plot of the total time and contribution of each component (FCR, customs clearance, verification, slot assignment) was generated to allows to clearly view of which links in the chain become bottlenecks in different scenarios, Figure 6.

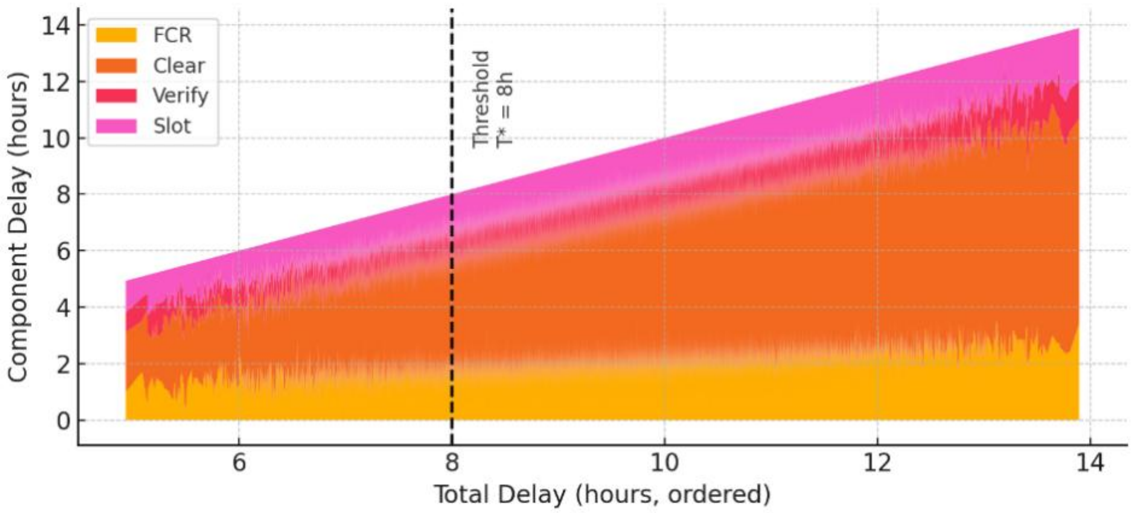

Fig. 6. Stacked component contributions to total delay

As can be seen from the graph, the largest amount of delays is generated by the customs clearance stage (T_{clear}), while the contribution of other procedures remains relatively small. The threshold of $T^* = 8$ hours clearly separates "acceptable" downtime from those that require urgent intervention to optimize the process.

To assess the risk of exceeding the permissible "grace period" depending on the choice of the threshold and the average customs clearance time, a contour graph is shown in Figure 7. It allows us to identify the parameters under which the probability of downtime becomes critical.

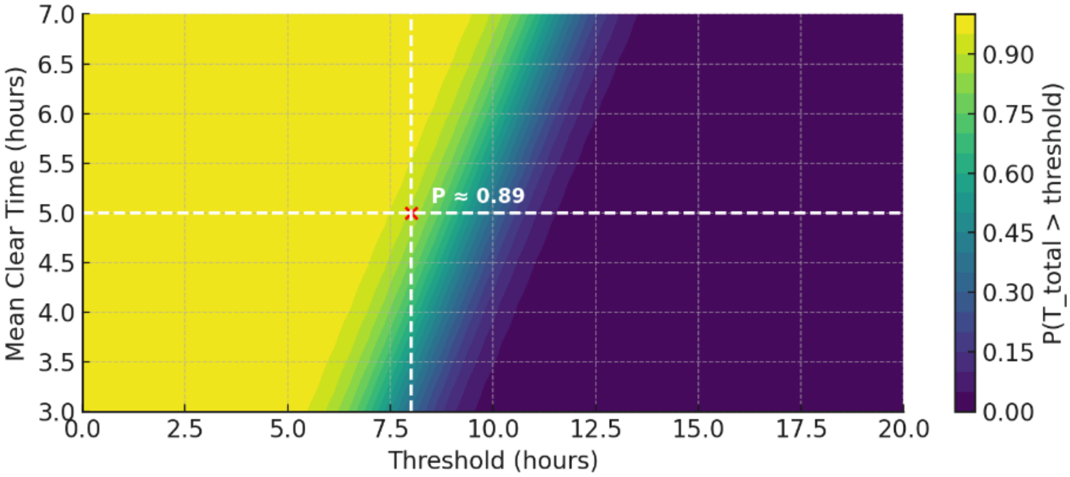

Fig. 7. Probability of exceeding the total delay depending on the threshold value and average customs clearance time

Probability of exceeding the threshold T_{total} as a function of Threshold (hours) and average customs clearance time (Mean Clear Time, hours). The white dashed lines mark the point (Threshold = 8 hours, Mean Clear Time = 5 hours) with P ≈ 0.89.

The contour plot shows that with an average customs clearance time of 5 hours, an increase in the threshold to 8 hours is accompanied by a probability of more than 89% of exceeding the "grace period". This confirms that reducing the average clearance time is an extremely effective way to reduce the risk of downtime.

To quantify the financial losses due to port delays, a graph was plotted in Figure 8 showing the expected cost of downtime (USD) as a function of simultaneous changes in the threshold value and average customs clearance time.

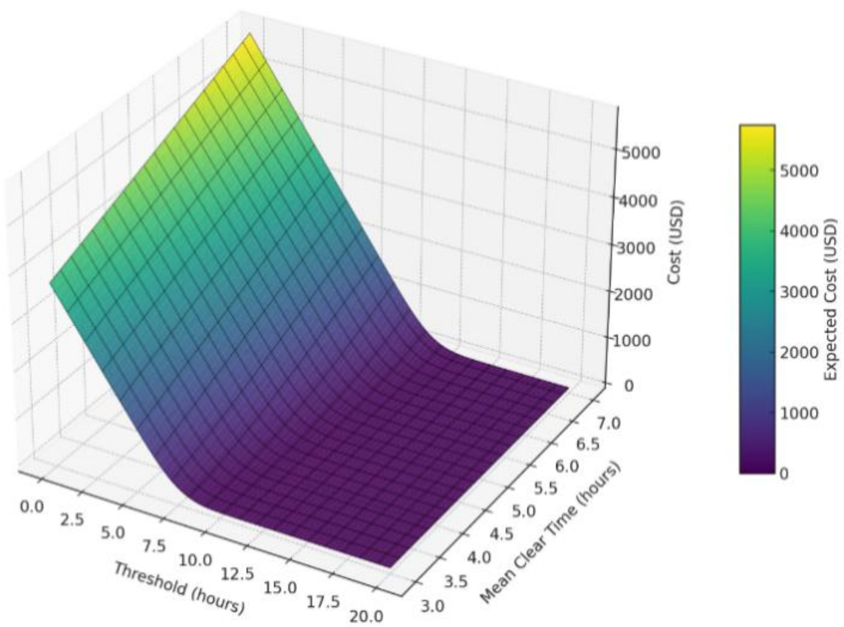

Fig. 8. Expected cost of vessel downtime (USD) as a function of threshold (hours) and Mean Clear Time (hours)

The graph shows that minimum costs are achieved at a threshold of about 5-6 hours with an average customs time of ≤4 hours. On the contrary, postponement of both parameters leads to a multiplicative increase in losses, and the cost of downtime can exceed 500,000 USD for extreme scenarios. This emphasizes the importance of simultaneously optimizing both parameters at the port.

4. DISCUSSION

During the analysis of document flow procedures in the Port of Tianjin, we found that the main bottlenecks are discrepancies between the FCR and the Shipping Order, delays in customs stamping, and manual verification of documents in PCS/TOS. Interviews with operators and statistical analysis have shown that the average time from issuing an FCR to assigning a berthing instruction can reach 12-16 hours, which significantly exceeds the regulatory "grace period" and leads to financial losses for shipowners and freight forwarders. At the same time, terminal practice has demonstrated the high efficiency of integrated APIs and automatic notifications, but these solutions cover only certain stages, while the lack of a single window slows down the final processing speed.

An economic analysis shows that the implementation of Single Window and automation of data transfer from FCR to Shipping Order will reduce total downtime by 8-10 hours and reduce the cost of vessel demurrage rates by approximately USD 4,500 per event. The combination of such technical solutions as rigorous data validation, blockchain audit, and SLA monitoring creates the preconditions not only for increasing speed but also for improving the transparency and reliability of the entire chain of logistics operations.

5. CONCLUSION

The analysis of the document flow in the port of Tianjin showed that the traditional two-stage mechanism - FCR as a confirmation of cargo acceptance and stamped Shipping Order as the basis for mooring - works correctly in the regulatory field of the PRC, but creates significant delays (up to 14-16 hours) due to data discrepancies, waiting for customs stamping, and manual checks in PCS and TOS. These delays lead to an increase in tariff costs for vessel downtime and exceeding the "grace period," which limits the port's throughput.

The proposed system of a single electronic window with automated exchange of FCRs and Shipping Orders, standardized exchange formats (XML/JSON, REST API), strict data validation, and blockchain audit will reduce the total time from issuing an FCR to a berthing instruction to 4-6 hours. This will save more than USD 540,000 in downtime tariffs and increase throughput by 5-7%, generating a few million in additional annual revenue.

The introduction of the Single Window, integration of customs and port IT systems, automatic alerts, and SLA monitoring will not only increase the efficiency and transparency of operations, but also lay the foundation for further digitalization of the port ecosystem - with the development of intelligent mooring planning algorithms, what-if analytics, and smart contracts on the blockchain. In this way, Tianjin Port will be able to strengthen its leadership position in the region and become a model of an efficient new generation smart harbor.

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Received 11.06.2025; accepted in revised form 15.09.2025