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ANALYSIS OF THE EFFICIENCY OF RAILWAY-WATER PRODUCTION LOGISTICS CHAINS BASED ON STOCHASTIC MODELING: METHODOLOGY AND EXPERIMENTAL RESEARCH

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Abstract – The article is devoted to the study of an improved intelligent stochastic model of the technology of functioning of rail-water production and transport logistics chains (PTLC) and to the study and analysis of effective scenarios of its application by integrating the model into the decision support system of operational logistics workers. The model of rail-water PTLC is based on the use of the Monte Carlo method, which takes into account the random nature of technological parameters. The model was verified with a check for adequacy through tests for stability, sensitivity to changes in input parameters and assessment of the variability of results. The proposed stochastic approach to modeling instead of a deterministic model allows us to take a real uncertainty of transport processes in the PTLC, assess risks through confidence intervals, compare not only the average values of costs, but also their variability, make decisions taking in the reliability of the forecast. Experimental simulation studies were conducted to identify patterns of optimal choice of delivery modes (normal, express or mixed strategy) depending on key factors. Critical thresholds and optimality zones were determined for various risk scenarios and effective technological boundaries of decision-making by operational workers in PTLC were found.
Key words – railway transport, intermodal transportation, intelligent transport technologies, stochastic transport processes, production and transport logistics chains
JEL Classification – C65, L91, L92, R41, R42

INTRODUCTION

The development of the transport industry in the context of large-scale aggression is constantly influenced by security challenges, which has led to a radical transformation of Ukraine's logistics chains. The destroyed traditional cargo routes, reduced transport infrastructure capacity and a serious shortage of port infrastructure against the background of the country's significant export dependence have made transportation management one of the main problems of the stability of the national economy. The node of interaction between rail and water transport in the system of production and transport logistics chains (PTLC) remains particularly critical [1]. One of the main problems in the operation of these chains is the high uncertainty of delivery time, which is formed under the influence of both usual logistical factors and military risks, which is manifested in additional costs due to long downtime of wagons and high costs for demurrage of vessels. Therefore, research through stochastic modeling will provide logistics specialists with an effective tool for choosing the optimal mode of delivery of goods by rail to ports in normal and accelerated (express) modes. This is of key importance for maintaining the competitiveness of Ukrainian manufacturers and ensuring the stability of national rail-water logistics chains. Thus, both from a scientific and practical point of view, theoretical and experimental research on innovative methods and approaches to optimize logistics efficiency is of great importance.

1. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Modern logistics chains are characterized by high complexity and dependence on the efficiency of each stage, especially at points of interaction and transshipment [1]. Multimodal transport is an important part of world trade, with the key element being the junction of rail and sea transport. At the same time, it is in ports and sea terminals that the main operational risks and opportunities for optimizing technological processes are concentrated [2].

The issue of forming logistics chains involving railways and other modes of transport is one of the most common in professional publications. Demurrage (a fee for the idleness of cargo or means of transport in the port beyond the agreed free time) is one of the most critical cost factors in modern maritime logistics chains. In [4] conducted an empirical study that showed that the reduction of free storage time of containers and the increase in fines for downtime is a long-term trend in the industry. It was found that the expansion of information systems of logistics companies and improved cooperation between cargo owners significantly reduces demurrage costs and improves the efficiency of logistics chains [3]. A comprehensive analysis of the global scale of demurrage has shown that it is not simply a financial loss from cargo delays, but a dynamic phenomenon with large annual costs that affects the very structure of the logistics industry and highlights the need for individualized strategies to optimize delays [4].

Minimizing demurrage costs requires a comprehensive approach that addresses root causes and risk factors through accurate planning, digital communication platforms, and optimized transport routes. Research shows that average demurrage and delay costs increased by 104% in 2021 due to port closures, congested supply chains, and driver/vehicle shortages [5].

Optimizing the interaction between rail and sea transport is a key direction for increasing the efficiency of intermodal transport. A systematic review of the literature highlights that the maritime and rail intermodal transport sector has gained significant advantages due to its low cost and better environmental performance. Many ports around the world have invested in rail terminals at seaports to improve the connection between rail and shipping areas [6].

A multi-objective mathematical model for optimizing rail-water transshipment operations is proposed in the source [7]. The model takes into account the features of the simultaneous operation of several parallel loading machines using intra-port trucks and flexible technological modes.

Taking into account the stochastic nature of logistics processes is critically important for making optimal decisions [8]. Authors in the source [9] showed that variability in order lead times does not always degrade supply chain performance, and only high levels of variability justify the need to create a coordinated supply chain. The study also found the need to use different hedging strategies to manage supply chain flows under stochastic lead times compared to the deterministic case.

The implementation of the developed models can be in the form of decision support systems to reduce the variability of order lead time and demand, demonstrating an increase in marginal savings in inventory costs from reducing all three variables: average lead time, demand variance, and lead time variance [10].

In the source [14] proposed to improve the business process of a cloud platform for combined rail-water transport, which provides a large amount of reliable information on real-time data exchange, connectivity and interaction for intermodal transport operators, railways, ports and shipping companies. This saves costs on business development time and increases business efficiency and security.

The coefficient of variation (CV) is widely used to compare the variance of variables with unequal means, which allows us to assess the stability of logistics systems under stochastic disturbances. In the source [13] shows that in the case of a delivery time with a high CV or high prediction error, it is necessary to work on reducing the order fulfilment time, while for a product with a low CV of delivery time, it is necessary to work on eliminating variability in the product delivery location.

Modern research emphasizes the importance of flexible mixed strategies in logistics. In particular, in the source [14] developed a stochastic mixed integer programming model to optimize express freight delivery by high-speed rail (HSR) trains to maximize net profit. The study considers integrated optimization problems, such as the ability to transport different types of freight by different modes and HSR trains.

Analysis of the sensitivity of logistics systems to changes in key parameters allows us to identify critical decision points. It is shown that the analysis of barriers to multimodal freight transport and their mitigation strategies is critical for the promotion of intermodal transport [15]. The study identified 31 barriers and possible strategies to overcome them, which are classified into six groups: Multifunction Terminal (MFT), MFT network, governance, regulation and subsidy, delivery characteristics and interaction between transport modes.

The main trends in the formation of international logistics in Europe are formulated in the European Commission Communication "Greening Freight Transport" (COM(2023)440), which defines a set of measures to decarbonize freight transport in the EU, increase its efficiency and competitiveness, and integrate different modes of transport into a single sustainable system [17]. The main idea of the document is to transition to more environmentally friendly modes of transport (rail, inland waterways, short sea shipping), digitalization of logistics and removal of regulatory barriers. The projected growth in freight turnover by +25% by 2030 and +50% by 2050 (compared to 2015) will be hindered by weak integration between modes of transport, infrastructure "bottlenecks" (ports, terminals, different track standards, etc.), as well as military operations in Ukraine have shown the need for sustainable logistics, which emphasizes the relevance of the proposed study [18].

Thus, despite the significant amount of research, there is a limited number of works that comprehensively integrate the analysis of critical thresholds of transportation cost increase relative to the capacity of port infrastructure, optimization of mixed delivery strategies taking into account infrastructure constraints and variability of delivery time. Of particular note is the consideration of the impact of military risks and extreme conditions on the optimality of logistics strategies, since most of the research was carried out for stable operating conditions. This study fills these gaps through comprehensive simulation analysis and experimental studies of the PTLC interaction model with the construction of optimal solutions for various risk scenarios and the determination of critical thresholds of system parameters.

2. DEFINING THE PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of this article is to develop an improved stochastic model of the technology of functioning of rail-water production and transport logistics chains (PTLC) and to study and analyze effective scenarios for its application. To achieve the goal, the following tasks have been defined:

- To develop a stochastic model of rail-water PTLC based on the Monte Carlo method, which takes into account the random nature of technological parameters;
- Verify and test the adequacy of the model through tests for stability, sensitivity to changes in input parameters, and assessment of the variability of results.
- Conduct experimental simulation studies to identify patterns in the optimal choice of delivery modes (normal, express, or mixed strategy) depending on key factors.
- Determine critical thresholds and optimality zones for different risk scenarios (low, moderate, high), find effective technological boundaries for decision-making by operational workers in the PTLC.

3. ANALYSIS OF THE EFFICIENCY OF RAILWAY-WATER PRODUCTION LOGISTICS CHAINS BASED ON STOCHASTIC MODELING

Analysis of the volume indicators of the work of JSC Ukrzaliznytsia shows that after the introduction of martial law, their decline was observed, but starting from 2024 there is a certain tendency towards stabilization and growth in transportation volumes (Fig. 1), which directly affects the intensity of work of PTLC, freight fronts on access tracks and ports [3]. Thus, a general economic trend is observed: the country's rail and water logistics system is adapting to new conditions, but remains vulnerable to geopolitical, economic, and military factors.

In studies [1-2] introduced the concept of a production and transport logistics chain, which refers to a system of logistics centers of various types of transport and a set of other logistics facilities (freight terminals, railway stations, ports, border crossing points, logistics technological and information infrastructure of consignors, consignees and logistics operators, etc.), which are functionally interconnected, have certain limitations on their own technical and technological capabilities and form a single integrity in order to achieve a synergistic effect from cargo delivery. The structural and logical scheme of the rail-water PTLC, which is the basis of the proposed stochastic model, is shown in Figure 2.

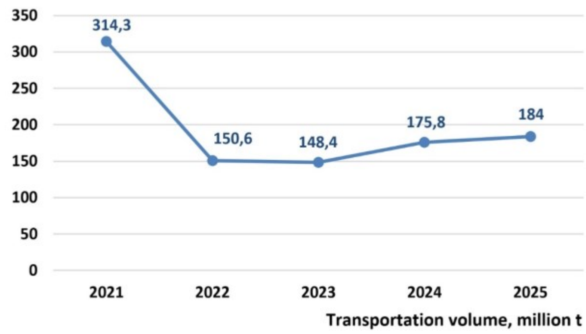

Fig. 1. Dynamics of railway transportation volumes in Ukraine (2021–2025, data [3])

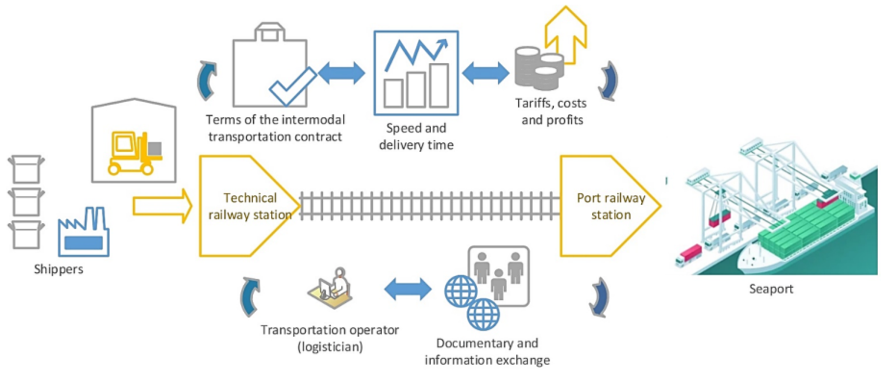

Fig. 2. Structural and logical diagram of the railway-water production and transport system logistics chain

Let us consider the process of functioning of PTLC as a system of cargo delivery from several manufacturers to a seaport with subsequent loading in the port onto a ship using cargo mechanisms (cranes). The delivery process can proceed in two main scenarios: normal mode (normal cargo speed) and express mode (high cargo speed), as well as a certain ratio of the share of cargo in each scenario simultaneously [18].

The PTLC model is characterized by the following input parameters, which are given in Table 1.

Table 1. Characteristics of input parameters of the PTLC model

Marking	Name
N	number of manufacturers (suppliers);
D	distance from the manufacturer to the port, km;
$Q_{судна}$	vessel capacity, t;
$q_{вагона}$	load capacity of one railway wagon, т;
τ_{norm}	average delivery time in normal mode, hours;
$\tau_{express}$	average delivery time by express mode, hours;
C_{norm}	normal delivery rate, UAH/(t·km);
$C_{express}$	express delivery rate, UAH/(t·km);
C_{wait}	cost of waiting car downtime, UAH/hour per car;
C_{demur}	cost of vessel downtime (demurrage), UAH/day;
M	number of cargo mechanisms (cranes) in the port;
μ	productivity of one loading mechanism (crane), t/h;
C_{crane}	cost of operating one crane, UAH/hour.

*For reference: on the time of publication, 40 UAH = 1 US dollars

The stochastic components of the PTLC model are the random number of wagons from each shipper (manufacturer) and the delivery time.

The random number of cars arriving from the i-th manufacturer is taken to be a discrete random variable with a uniform distribution with a maximum number U_{max}

$$n_i \sim U(1,\ U_{max}),\ \ i = 1,\ 2,\ \dots,\ N \tag{1}$$

Then the total weight of the cargo from the i-th manufacturer:

$$W_i = n_i \cdot q_{wag} \tag{2}$$

The stochastic delivery time in the basic version of the model is assumed to obey a normal distribution, which corresponds to the peculiarities of transport processes. For normal and express scenarios, the speed of cargo delivery

$$\begin{gathered} T_i^{norm} \sim N(\tau_{norm},\ \sigma_{norm}^2) \\ T_i^{express} \sim N\left(\tau_{express},\ \sigma_{express}^2\right) \\ T_i^{norm},\ T_i^{express} > 0 \end{gathered} \tag{3}$$

where: $\tau_{norm,}$, $\tau_{express}$ – mathematical expectation of cargo delivery time to the port, hours;

σ_{norm}, $\sigma_{express}$ – standard deviation of delivery time.

The use of the normal distribution (3) for estimating delivery times is proposed in normal conditions, since it poorly takes into account the risks of extreme delays. Military risks, destruction of infrastructure, force majeure, etc. create transport delays (extreme risks), i.e., a right-sided asymmetry of the distribution density function. This means that the probability of significant delays is higher than arriving ahead of schedule. Therefore, for martial law conditions, it is recommended to use the lognormal distribution $T_i \sim Lognormal\left(\tau_{i,}\ \sigma_i^2\right)$ or Weibull distribution $T_i \sim Weibull\left(\tau_{i,}\ k_i\right)$.

Total cost of transportation by PTLC from all manufacturers

$$C_{transport} = \sum_{i=1}^{N} W_i \cdot D \cdot C_{rate} \tag{4}$$

where $C_{rate}=C_{norm}$ *or* $C_{express}$ depending on the selected mode and is calculated according to the current tariffs and standards of JSC "Ukrzaliznytsia".

The problem with rail-water PTLC is that the cargo capacity of a ship Q_{ships} and a railway wagon q_{wag} differs many times. Therefore, either there is a queue of wagons for reloading at the port (pre-port) station, or the wagons are used as a "warehouse on wheels" [4-5]. Due to the decision of the operational staff to choose the normal $\mathbb{E}[C_{norm}]$ and express $\mathbb{E}\left[C_{express}\right]$ scenarios of cargo delivery speed, this negative phenomenon is significantly reduced and cost savings are achieved by reducing the duration of the car's stay in the PTLC.

The wagons arrive at the port at random times T_i. After sorting by arrival time, a queue with a wait is formed. Taking into account the random waiting time for $t_{wait}^{(i)}$ the i-th shipment in the queue, the costs associated with waiting for the wagons will be:

$$C_{wait}^{(i)} = t_{wait}^{(i)} \cdot n_{(i)} \cdot C_{wait} \tag{5}$$

Cargo loading onto the ship is carried out by cargo devices (cranes), while the cranes M operate in parallel and will have a cost of $C_{crane}^{(i)}$. If the current time after servicing the i-th shipment is $t_{current}^{(i)}$, then the total time of servicing the ship will be equal to $T_{total} = t_{current}^{(N)}$, when all current cargo in the wagons has been processed. Then the cost of demurrage (ship downtime):

$$C_{demur} = \frac{T_{total}}{24} \cdot C_{demur} \tag{6}$$

Thus, the overall objective function of the model with the choice of minimum costs depending on the scenario has the form

$$C_{total} = \left\{ C_{transport} + \sum_{i=1}^{N}\left[C_{wait}^{(i)} + C_{crane}^{(i)}\right] + C_{demur}\,;\, \begin{bmatrix} \mathbb{E}[C_{norm}], \\ \mathbb{E}\left[C_{express}\right] \end{bmatrix} \right\} \rightarrow min \quad (7)$$

To make a decision on the choice of delivery mode, the method of statistical testing (Monte Carlo) is used, a sufficiently large number of simulations (*K≫100*) are performed for each scenario with the establishment of the optimal one $\mathbb{E}^{*}= arg\ min \left\{\mathbb{E}\ [C_{norm}],\ \mathbb{E}\left[C_{express}\right]\right\}$.

The developed model of rail-water PTLC assumes simultaneous readiness of cargo for shipment (t= 0) at all manufacturers, and the ship arrives at the port simultaneously with the first wagons. In real conditions, the shipment process has a discrete-continuous nature, which can be taken into account by introducing a random value of the departure interval. The model considers the productivity of crane equipment as a deterministic value μ, i.e. cranes operate continuously and with constant productivity, without taking into account possible technical failures or weather restrictions. It is also assumed that cranes operate with a common cargo queue, the cargo is distributed evenly between the available cranes without division by berths or by type of cargo. These assumptions do not change the general logic of the proposed scenario selection method, but determine the directions for further improvement of the PTLC model.

The proposed stochastic approach to modeling instead of a deterministic model allows us to take into account the real uncertainty of transport processes in the PTLC, assess risks through confidence intervals, compare not only the average values of costs, but also their variability, and make decisions taking into account the reliability of the forecast.

To make a decision on the choice of delivery mode, the statistical testing method (Monte Carlo) is used as follows:

- K simulations (*K≫100*) are performed for each scenario.
- For each simulation k, the total costs $C_{total}^{(k)}$ are calculated using the formula (7).
- For each scenario, the statistical characteristics $C_{total}^{(k)}$ are calculated: mathematical expectation, variance, and coefficient of variation v_c. The latter is used to assess the reliability of the modeling results. It is assumed that when v_c < 10%, we have high reliability of the result, when 10% ≤ v_c < 20% - moderate variability, and when v_c ≥ 20% - high uncertainty.
- The next step is the selection of the optimal scenario. The delivery scenario with the minimum expected cost is selected

$$\mathbb{E}^{*}= arg\ min \left\{\mathbb{E}[C_{norm}],\ \mathbb{E}\left[C_{express}\right]\right\} \quad (8)$$

- Finally, the savings from choosing the optimal delivery scenario are calculated:

$$\Delta C = \left|\mathbb{E}[C_{norm}] - \mathbb{E}\left[C_{express}\right]\right| \quad (9)$$

The adequacy of the model was tested through a robustness test (convergence $\mathbb{E}[C]$ when increasing *K*), a sensitivity test (by analyzing the influence of input parameters on the result), and a comparison of vs (lower variability indicates greater reliability of the result). It is desirable to present the results of the model adequacy verification and to provide them in a more detailed form, supported by specific calculation results.

For verification purposes, a simulation of a conventional rail-water PTLC was conducted using average performance indicators of JSC "Ukrzaliznytsia" and some ports, taken from open sources. It is necessary to clearly indicate which specific rail-water PTLC routes were used as the basis for the calculations, including the presentation of their concrete (numerical) parameters. In other words, the authors should provide the input data used for the modeling.

In order to identify the conditions and patterns under which optimal technological parameters of production and transport logistics chains (PTLC) can be achieved, a simulation was conducted, where key input parameters were varied.

For the verification, a simulation of a conventional rail-water PTLC was conducted using the average performance indicators of JSC "Ukrzaliznytsia" and some ports, taken from open sources, with the following parameters: 3 manufacturers participate in the PTLC, loading is carried out on a Panamax class vessel with a deadweight of 60,000 tons, two cranes are operating. It was obtained that the scenario $\mathbb{E}[C_{norm}]$ with normal speed gives costs C_{total} at the level of 1.84 million UAH with an average time of the vessel under load T_{total} = 37.8 hours. The scenario $\mathbb{E}[C_{express}]$ with express delivery speed gives costs 2.16 million UAH with T_{total} = 28.1 hours. In this case, the optimal scenario is the scenario with normal speed, which gives 0.32 million UAH of savings per vessel. The suboptimal application of the express transportation scenario is due to the fact that the time savings from accelerating the movement of wagons and reducing demurrage are absorbed by the high railway tariff.

A two-dimensional sensitivity analysis to restrictive and economic factors was implemented on conditional, close to real data. This experiment aims to investigate the interaction of two key factors that determine the efficiency of a logistics chain:

- Infrastructure constraints (number of cranes, M): a factor that affects the speed of cargo handling in the port (t_{load}) and, consequently, the total downtime of the vessel.
- Financial risk (cost of vessel downtime (demur): a factor that magnifies the consequences of vessel downtime, making it the most sensitive cost element.

By constructing a matrix of optimal solutions, the optimality zone for normal and express is determined cargo delivery speed scenarios for each combination of M (1 to 5) and C_{demur} (10,000 to 50,000 UAH/day). The decision criterion is the choice of the mode that provides the minimum expected total costs argmin{E [C_{norm}], $\mathbb{E}[C_{express}]$}. In results simulation yielded an optimality matrix, which is given in Table 2. The expected costs in the PTLC system for both scenarios are given in Figure 3.

Table 2. Matrix for selecting optimal delivery modes

$M \backslash C_{demur}$ (thousand UAH/day)	10	20	30	40	50
1 crane	**Espresso**	**Espresso**	**Espresso**	**Espresso**	**Espresso**
2 cranes	Normal	**Espresso**	**Espresso**	**Espresso**	**Espresso**
3 cranes	Normal	Normal	**Espresso**	**Espresso**	**Espresso**
4 cranes	Normal	Normal	Normal	**Espresso**	**Espresso**
5 cranes	Normal	Normal	Normal	Normal	**Espresso**

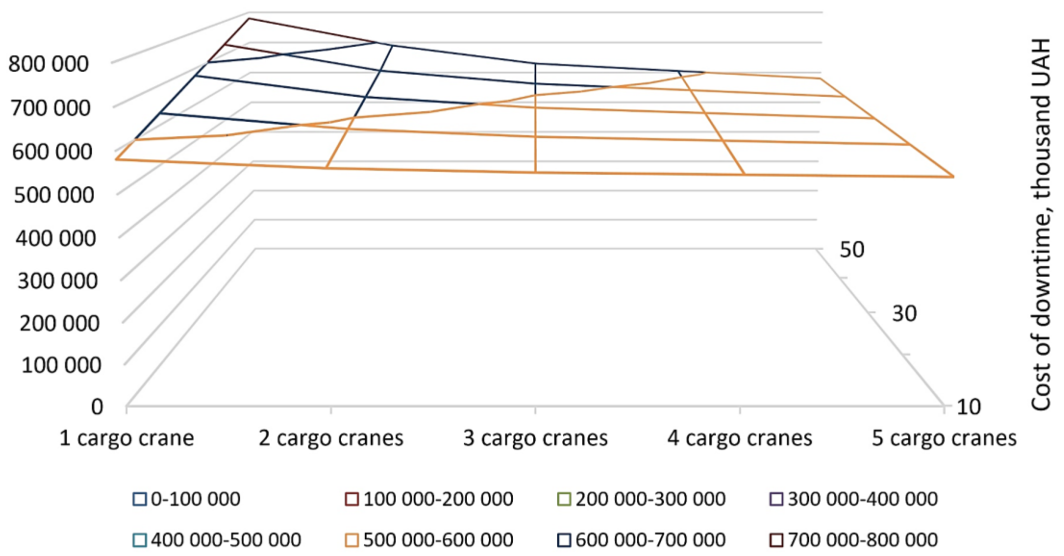

Fig. 3. Expected optimal costs in the PTLC system (UAH/day) for normal and express cargo delivery speed scenarios

Two-dimensional analysis clearly shows that optimal regime is not simply a result of high or low cost, but a trade-off between financial risk (C_{demur}) and infrastructure capacity (*M*). The express regime dominates at low M and high C_{demur}, which is typical for modern Ukrainian ports with limited resources and high military risks. To switch to the cheaper normal regime, it is necessary either to have a high number of cranes (e.g., M ≥ 4 at C_{demur} = 30 thousand), or to have a low demurrage cost (e.g., C_{demur} ≤ 20 thousand at M = 3).

Sensitivity analysis to delivery time variability is critical for assessing financial risk and aims to determine how an increase in the standard deviation (σ) of delivery time, which models increased logistical volatility, affects the financial stability of total costs, measured through the coefficient of variation (*CV*) for fixed parameters *M* and C_{demur}

$$\mathrm{CV}=\frac{\sqrt{Var[C]}}{\mathrm{E}[C]} \tag{10}$$

The choice of the most predictable and stable mode corresponds to the minimization of *CV*, the results are shown in Figure 4.

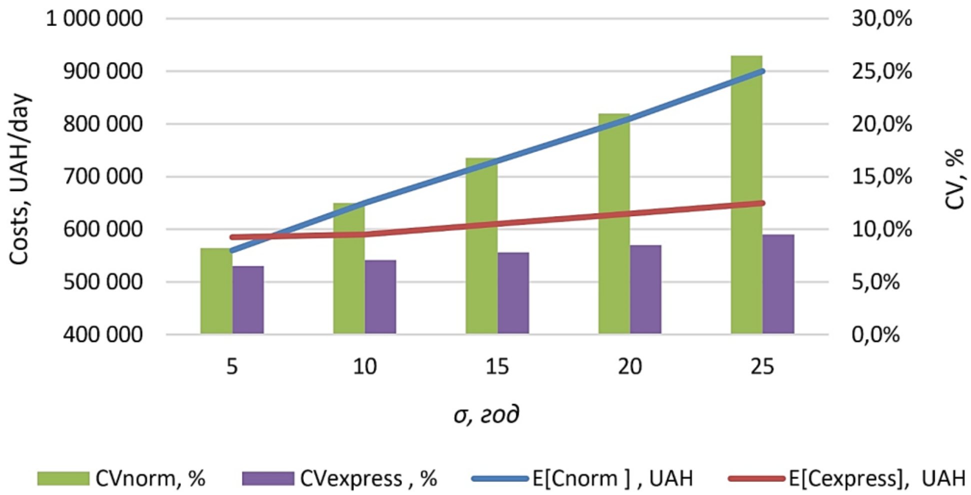

Fig. 4. Results of selecting the most predictable and stable mode for normal and express cargo delivery speed scenarios

Analysis of the results showed the presence of instability in the normal scenario: with increasing σ, increases exponentially CV_{norm} (from 8.2% to 26.5%). This means that by choosing the normal mode in unpredictable conditions, the logistician assumes a significant and growing financial risk of unexpected peak losses due to demurrage. The stabilization function of the express scenario $CV_{express}$ remains relatively low and less sensitive (growth of only 9.5%). This proves that the express regime, despite the higher tariff, is a stabilizer of financial risk, guaranteeing greater predictability of final costs in PTLC.

To make operational decisions on the choice of the PTLC operating mode, it is important to optimize the mixed strategy (balance of quantity *M* and share $P_{express}$) for different C_{demur} in order to minimize the total costs of the mixed strategy $\mathrm{E}[C_{total}]$. Three levels of vessel downtime cost (C_{demur}) are considered:

- Low risk, scenario A: C_{demur} = 10,000 UAH/day
- Moderate risk, scenario B: C_{demur} = 30,000 UAH/day (baseline scenario)
- High risk, scenario B: C_{demur} = 50,000 UAH/day (relevant for wartime conditions)

As a result of the analysis of the obtained simulation data for scenario A, it was established (Table 2) that the risk is low (low demurrage cost), the financial pressure on the system is minimal, and the transport tariff becomes the key factor. In this case, the normal mode dominates, so the optimal strategy is a pure normal strategy ($P_{express}$=0%) regardless of the port power. This is due to the fact that fines for downtime are low and it makes no economic sense to pay an increased transport tariff for express delivery.

The baseline scenario is scenario B, where the risk of vessel downtime is significant but manageable (Table 3).

In this case, a mixed strategy dominates: at low and moderate capacity (M = 2, 3, 4) $P_{express}$=25% is optimal. Partial use of express delivery is economically justified to protect against moderate risk of demurrage and to provide a small buffer of express speed wagons to avoid peak delays. Port capacity saturation ($M \geq 5$) leads to the fact that pure normal mode ($P_{express}$=0%) becomes optimal in PTLC.

Scenario B is characterized by high risk and high financial pressure on the parameters of the PTLC, which corresponds to the conditions of military risks and high freight costs (Table 3). There is a dominance of express delivery: with increasing financial risk, the optimal share of $P_{express}$ increases sharply. At M = 2 (critical bottleneck), it is optimal to use $P_{express}$ = 75% of express delivery to minimize catastrophically high demurrage. At $M \geq 3$, it is optimal to use $P_{express}$ = 50% of express delivery. Indeed, in this scenario, the cost of demurrage becomes so high that it outweighs the difference in transport tariffs. It is more profitable for the PTLC to decide to pay a more expensive tariff for a larger part of the cargo to guarantee fast arrival and minimize the most expensive cost component - vessel downtime.

Table 3. Cost analysis by delivery mode options for scenarios with different risks, thousand UAH/day

$M\backslash P_{express}$, %	0%	25%	50%	75%	100%	Optimal proportion $P_{express}$
Low risk, scenario A						
2 cranes	**550**	560	570	580	590	**0%**
3 cranes	**510**	520	530	540	550	**0%**
4 cranes	**490**	500	510	520	530	**0%**
5 cranes	**480**	490	500	510	520	**0%**
Moderate risk, scenario B						
2 cranes	750	**620**	645	675	700	**25%**
3 cranes	650	**605**	615	625	650	**25%**
4 cranes	570	**565**	568	572	575	**25%**
5 cranes	**540**	545	550	555	560	**0%**
High risk, scenario B						
2 cranes	950	790	730	**710**	715	**75%**
3 cranes	800	690	**650**	660	670	**50%**
4 cranes	730	620	**580**	590	600	**50%**
5 cranes	670	580	**550**	560	570	**50%**

Thus, the need for a mixed strategy arises at relatively low and moderate port capacity, the optimal solution is to use 25% express mode. This allows to smooth out peak delays in the arrival of wagons and minimize demurrage, while avoiding excessive costs for 100% express tariff. The effect of system saturation occurs at high capacity: in this case, pure normal mode ($P_{express}$ =0%) becomes optimal, since the port is able to handle cargo efficiently, so the investment in a more expensive express tariff becomes economically unjustified.

In order to analyze the sensitivity of PTLC to the relative increase in the price of express transportation, the dependence of total costs on the average delivery time (τ) and variance (σ) was studied, i.e. $\tau_{express} < \tau_{norm}$, which is the main advantage of the express scenario. It is this difference that leads to a lower average vessel downtime (t_{demur}) for the express mode, and therefore lower total demurrage costs ($C_{demur} \cdot t_{demur}$). The study was performed under the basic conditions of moderate risk (C_{demur} = 30,000 UAH/day) in order to determine the critical percentage of the increase in the price of the express tariff (ΔC %), at which the marginal savings on demurrage cease to compensate for the more expensive railway tariff (see Table 4).

It is found that the normal mode costs $\mathrm{E}[C_{norm}]$ are constant when $C_{express}$ changes, and depend only on the quantity M, while the expected total express mode costs $\mathrm{E}[C_{express}]$ show a linear increase with increasing tariff.

The critical element in the PTLC is the port capacity. At M=2 (low capacity), the port is a clear “bottleneck”. The express mode remains profitable (as long as $\Delta\mathrm{E}[C] > 0$), even if its cost has increased by 60%. The critical threshold (the point where $\Delta\mathrm{E}[C] \approx 0$) is between 60% and 80%. At M=3 (moderate capacity), the port is a less critical node, so the sensitivity threshold drops. The express mode loses its advantage when its cost increases by 40% of the cost of the normal delivery mode. At *M*=4, 5 (sufficient capacity), the normal mode becomes more profitable even with a minimal increase in the express tariff (ΔC% < 20%). This means that as soon as the port infrastructure solves the problem of downtime, the choice of delivery mode completely shifts to the plane of minimizing transport costs.

Thus, it was established that the critical threshold for increasing the price of express delivery compared to normal is inversely proportional to the capacity of port *M*. The weaker the infrastructure, the greater the premium (up to 80%) the PTLC logistician is willing to pay for the speed of delivering wagons to the port in order to avoid high and unstable demurrage costs, which are created precisely due to insufficient cargo processing speed.

Table 4. Cost analysis by delivery mode options for percentage increase in express rate compared to normal (ΔC%)

$M\backslash\Delta C$% (Increase in $C_{express}$)	**20%**	**40%**	**60%**	**80%**	**100%**
Normal delivery mode $\mathrm{E}[C_{norm}]$, thousand UAH/day					
2 cranes	750	750	750	750	750
3 cranes	650	650	650	650	650
4 cranes	570	570	570	570	570
5 cranes	540	540	540	540	540
Express delivery mode $\mathrm{E}[C_{express}]$, thousand UAH/day					
2 cranes	610	670	730	790	850
3 cranes	590	650	710	770	830
4 cranes	580	610	640	670	700
5 cranes	570	580	590	600	610
Cost difference $\Delta\mathrm{E}[C] = \mathrm{E}[C_{norm}] - \mathrm{E}[C_{express}]$, thousand UAH/day (A positive value of $\Delta\mathrm{E}[C]$ means that the express mode is more profitable; a negative value means that the normal mode is more profitable)					
2 cranes	**+140**	**+80**	**+20**	-40	-100
3 cranes	**+60**	**0**	-60	-120	-180
4 cranes	-10	-40	-70	-100	-130
5 cranes	-30	-40	-50	-60	-70

Under these conditions, it becomes necessary to investigate the sensitivity to the relative advantage (acceleration) of express speed over time (*M* and $\Delta\tau$%). To do this, the minimum required advantage in speed ($\Delta\tau$%) of the express mode is determined, which is necessary for it to become economically profitable (minimize total costs $\mathrm{E}[C_{total}]$) *at different fixed percentages of increase in the express tariff ΔC% and different port capacity M*. The cost difference $\Delta\mathrm{E}[C] = \mathrm{E}[C_{norm}] - \mathrm{E}[C_{express}]$ is used to identify the critical threshold (Fig. 5). It is established that at a fixed ΔC% = 40%, the critical threshold of the relative advantage (acceleration) of express speed over time $\Delta\tau$% decreases. If the port is a critical node (*M* = 2), a very high gain in speed (about 50%) is required to justify the increase in price by ΔC% = 40%. Once *M* increases to 3 or more, the need for speed gain drops to 20%.

As the price premium ΔC% increases from 40% to 60%, the required minimum speed gain $\Delta\tau$% to maintain the optimality of the express mode increases almost linearly. If the port capacity is weak (*M* = 2), then for a ΔC% = 60% price increase an extremely high speed is required ($\Delta\tau$% ≈ 80% faster than normal). This emphasizes that the infrastructure bottleneck must be eliminated, since it is almost impossible to provide such a large speed advantage. The value for $M \geq 4$ is strategic: if the port is powerful, then to justify a ΔC% = 60% price increase in the tariff, a speed gain of only $\Delta\tau$% 30% – 40% of normal is required. This proves that with the elimination of the downtime problem, the system becomes much more sensitive to the time gain and even a small speed increase can have a decisive impact.

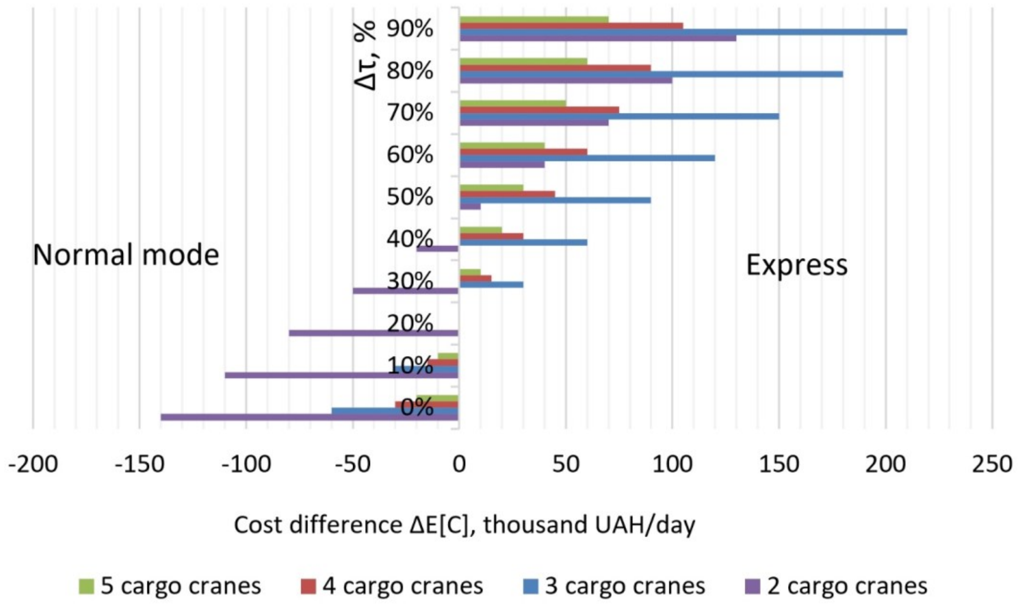

Fig. 5. Results of selecting the optimal mode Δτ% of PTLC operation for normal (left) and express scenarios (right) of cargo delivery speed

CONCLUSIONS

In progress to the integration of railway, sea and other modes of transport, and the availability of developed infrastructure, intermodal transportation in Ukraine is actively developing. Despite the current situation in the country, the issue of forming effective rail-water intermodal transport networks in the context of intellectualization of technological processes and creating favorable conditions for the post-war development of industry and the transport sector is relevant.

A proposed stochastic model of rail-water transport PTLC takes into account the real uncertainty of transport processes, and also allows to assess risks through confidence intervals of random technological indicators. This allows to put this approach to the formation decision support systems (DSS) of operational workers taking into account the reliability of the forecast.

As a result of the conducted simulation experiment on the study of PTLC, the patterns of optimal choice of cargo delivery modes when varying the key parameters of the system were established. The optimal mode of operation of PTLC is determined by a compromise between the capacity of the port infrastructure (number of cranes M) and the cost of vessel downtime (C_{demur}), and not by the absolute values of these parameters. It was established that the express mode dominates at low port capacity and high demurrage costs, which corresponds to the conditions of modern Ukrainian ports with limited resources and increased military risks.

Sensitivity analysis to the variability of delivery time revealed a critical difference in the financial stability of the modes. With an increase in the standard deviation of delivery time, the coefficient of variation of the normal mode increases very intensively (from 8.2% to 26.5%), while for the express mode the *CV* remains stable. This proves that the express mode performs the function of a stabilizer of financial risk, guaranteeing the predictability of costs in the PTLC even with high uncertainty of logistics processes.

The study confirmed the optimality of mixed strategies and the need for a differentiated approach to choosing a strategy depending on the level of risk: at low risk, a pure normal strategy is optimal regardless of the port capacity, at moderate risk, a mixed strategy with partial use of express delivery dominates, at high risk, express delivery dominates. The mixed strategy allows smoothing out peak delays in the arrival of wagons and minimizing demurrage, while avoiding excessive costs for the express tariff. On the other hand, this means that the weaker the infrastructure, the greater the premium (up to 80%) the logistician is willing to pay for the speed of delivery to avoid high and unstable costs for demurrage. Sensitivity analysis of the relative advantage of express speed showed that the minimum required speed advantage $\Delta\tau\%$ decreases with increasing port capacity.

Thus, based on the results of the study, it is proven that with limited resources, investments in increasing port capacity (increasing the number of cranes) are critically important. In conditions of high uncertainty (wartime, logistical crises), it is advisable to increase the share of express delivery to 50-75%, and the optimal strategy should be dynamic and take into account the current values of all three key parameters: demurrage cost, port capacity and additional payment (premium) for speed of delivery.

The results of the study have both theoretical significance for the development of the theory of optimization of logistics chains under conditions of uncertainty, and practical value for the operational management of transport and logistics companies, especially in the context of functioning in conditions of increased risks.

AUTHOR CONTRIBUTIONS

– conceptualization, D.L. (Denis Lomotko), V.I. (Vasyl Ilchyshyn), D.A. (Danylo Arsenenko), M.L. (Mykola Lomotko), O.A. (Olga Afanasova);
– methodology, D.L.;
– validation, V.I. and D.A.;
– formal analysis, M.L.;
– investigation, D.L., V.I., D.A., M.L. and O.A.;
– writing - original draft preparation, M.L. and O.A.;

All authors have read and agreed to the published version of the manuscript.

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