МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ НАДІЙНОСТІ ЗМІЩАНИХ ПЕРЕВЕЗЕНЬ ВАНТАЖІВ ЗА ДИНАМІЧНОЇ ЗМІНИ УМОВ.

Актуальність. Військові загрози обумовили значні темпи змін ризиків транспортування змішаних вантажів і довели необхідність нових методів забезпечення надійності перевезень. Найперше постало проблема оцінювання рівня надійності транспортування за окремими маршрутами та моделювання можливої зміни маршрутів з вибором більш безпечних варіантів та шляхів перевезень. Особливо важливою функцією такої моделі, обумовленою швидкими темпами зміни ризиків стає можливість її практичного застосування в умовах реального часу.

Мета та завдання. Метою роботи є розробка математичної моделі змішаних перевезень вантажів в умовах динамічної зміни ризиків для збільшення надійності транспортного процесу, аналізу альтернативних варіантів перевезення та виявлення можливостей зміни маршрутів навіть в процесі перевезення вантажу. Дослідження мети дослідження зумовлює необхідність використання альтернативних методів для виявлення можливостей зміни маршрутів в реальному часі; доведення можливості розробленої моделі на прикладі конкретних вантажів; забезпечення прогнозування надійності наступних етапів транспортування вантажу; реалізації можливостей оптимізації багатоцільових задач для забезпечення надійності, мінімізації вартості та часу перевезення; проведення стратифікації надійності перевезення вантажів за рівнем ймовірності загроз.

Матеріали та методи. В роботі застосовувалися різні загальні та спеціальні методи пізнання: методи кількісного та якісного порівняння для виявлення можливості зміни перевезення вантажів в залежності від ризиків на окремих етапах; методи векторного аналізу для врахування ймовірності ризику транспортування вантажів за кожним етапом змішаного перевезення; метод індукції й дедукції дозволяє розглянути надійність перевезення як величину, зворотню вірогідності ризику перевезення; метод фрагментации задачі дозволяє включати вірогідні етапи перевезення в різні транспортні маршрути; метод математичної формалізації задачі для формування моделі змішаних перевезень вантажів з використанням водного транспорту в умовах динамічної зміни ризиків.

Результати. Розроблена математична модель змішаних перевезень вантажів в умовах динамічної зміни ризиків для збільшення надійності транспортного процесу, аналізу альтернативних варіантів перевезення та виявления можливостей зміни маршрутів в процесі перевезення вантажу. Для цього використання використання моделі змішаних перевезень вантажів Північно-Західного регіону, використання моделі змішаних перевезень вантажів Північного регіону, використання моделі змішаних перевезень вантажів Північного регіону, використання моделі змішаних перевезень вантажів Північного регіону.

Висновки. За використання моделі проаналізовано діяльність підприємств, які транспортували свою продукцію через порти Азовського моря. За зменшення надійності перевезень вантажів Керченською протокою запропоновано альтернативні маршрути транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршрути транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршрути транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршрути транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршруті транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршруті транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршруті транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршруті транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршруті транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршруті транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів використання моделі змішаних перевезень вантажів Керченською протокою запропоновано альтернативні маршруті транспортування змішаних вантажів, за використання на окремих етапах суден «ріка-море». Апробація моделі змішаних перевезень вантажів
Mathematical modeling of the reliability of mixed cargo transportation under dynamic change of conditions.

Topicality. Military threats determined the significant pace of changes in the risks of mixed cargoes transportation and proved the need for new methods of ensuring the reliability of transportation. First of all, there was the problem of assessing the levels of transportation reliability along individual routes and modeling a possible change of routes with the choice of safer options and ways of transportation. A particularly important function of such a model, due to the rapid pace of changes in risks, is the possibility of its practical application in real-time conditions.

Aim and tasks. The purpose of the work is to develop a mathematical model of mixed cargo transportation in the conditions of dynamic changes in risks to increase the reliability of the transportation process, analyze alternative options for transportation, and identify opportunities for changing the route even in the process of cargo transportation. Achieving the goal of the study made it necessary to set and solve the following tasks: to implement the possibility of analyzing alternative transportation options and proposing route changes in real time; prove the capabilities of the developed model on the example of specific enterprises; to ensure reliability forecasting of the next cargo transportation stages; implement the possibility of optimizing multi-purpose tasks to ensure reliability, minimize the cost and time of transportation; to stratify the reliability of cargo transportation according to the level of threats probability.

Materials and methods. Various general and special methods of knowledge were used in the work: the method of quantitative and qualitative comparison for the stratification of the cargo transportation reliability depending on the risks at individual stages; methods of vector analysis to take into account the probability of the cargo transportation risk at each stage of mixed transportation; the method of induction and deduction made it possible to consider the reliability of the transportation as the reciprocal of the transportation risk probability; the task fragmentation method allows to include probable stages of transportation in different transport routes; a method of mathematical formalization of the problem for the formation of a model of mixed cargo transportation using water transport in conditions of dynamic changes in risks.

Research results. A mathematical model of mixed cargo transportation in conditions of dynamic changes in risks was developed to increase the reliability of transportation, analyze alternative transportation options, and identify opportunities for changing the route during cargo transportation. To solve this, the following tasks were developed: a mathematical model capable of analyzing alternative transportation options and proposing route changes in real life was developed; proven possibilities of the model on the example of specific enterprises; forecasting of the reliability the next cargo transportation stages is ensured; the possibility of optimizing multi-purpose tasks to ensure reliability, minimizing the cost and time of transportation has been implemented; stratification of the reliability cargo transportation by the level of probability threats was carried out.

Conclusion. Using the model, the activities of enterprises that transported their products through the ports of the Sea of Azov were analyzed. Due to the decrease in the reliability of cargo transportation through the Kerch Strait, alternative routes for the transportation of mixed cargo are proposed, for the use of "river-sea" vessels at certain stages. Approximation of the model for increasing the efficiency of the transport and logistics process of enterprises proved its effectiveness. The use of the developed mathematical model for the analysis of enterprise activity indicated an implicit advantage of increasing the level of transportation reliability, in particular, in relation to identifying the possibility of reducing warehouse stocks with a significant saving of working capital at the same time. The presented results of the research make it possible to ensure the proper reliability of transportation of mixed cargoes, even in conditions of significant dynamic changes in the level of threats on transportation routes.

Keywords: mixed transportation, target function of reliability, mathematical model, dynamic change of risks.
Problem statement and its connection with important scientific and practical tasks. The problem of dynamic changes in the risks of mixed cargo transportation has long been overlooked by both the scientific community and practitioners. Under conditions of peace, dynamic changes are characteristic only of weather risks, and these risks, with a significant level of reliability, are able to predict meteorological services. The war in Ukraine caused significant changes in the risks of cargo transportation and proved the need for new approaches to ensuring the reliability of transportation. First of all, there was the problem of assessing the levels of reliability of transportation along individual routes and modeling a possible change of routes with the choice of safer options and ways of transportation. When conducting mathematical modeling, the choice of reliability of transportation as the main objective function does not exclude the need for optimization according to objective functions of the second order, for example, the cost and time of cargo transportation. It should also be taken into account that the rates of change in risks due to military operations are so high that the threat may arise already in the process of cargo transportation, after passing through the initial stages of the transport chain. When developing mathematical models of mixed cargo transportation in conditions of dynamic changes in risks, one should also take into account the need to ensure the forecast function. The absence of such a function significantly reduces the practical value of the mathematical model, since only the formation of a forecast of the reliability value of cargo transportation at the next stages of transportation will provide an opportunity to offer alternative, currently safer, transport routes.

This significantly complicates the task of building relevant mathematical models to solve the specified problem and causes strict requirements for them.

Analysis of recent publications on the problem. Many scientists have devoted their works to the study of the impact of the risks of mixed transportation, including the use of water transport: O.M. Kibik, T. A. Vorkut, O. Ye. Bilonoh, Yu.F. Kulaiev, N.H. Metelenko, A.P. Petrov, V.O. Rybalkin, Yu.M. Tsvietov, V.H. Chekalovets, I. O. Tkachenko etc. The problem of risk management was studied by scientists: Goerlandt, 2015; Ilchenko, 2017; Karpenko, 2018; Tarashevskyi, 2020; Zahorodnia, 2021; Xiong, 2014; Wassan, 2008. During the last time, they devoted their scientific works to the problems of modeling mixed transportation Charoennapharat, 2022; Hryhorak, 2020; Chang, 2019; Nguyen, 2020. Including dynamic changes in risks: Bazaluk, 2021; Aulin, 2020; Kotenko, 2022. In the presented work, the results of calculations of the reliability of cargo transportation through the ports of the Sea of Azov in 2018-2022 before the start of large-scale military operations were used, provided in the work (Kotenko, 2022).

Allocation of previously unsolved parts of the general problem. The existing development of mathematical models for ensuring the reliability of transportation at a significant rate of change in threats still requires significant time resources for calculations, and often this time is greater than the time the vehicle enters the dangerous stage of the logistics route. This complicates the analysis of alternative options for transportation routes and the timely provision of forecasts regarding dangerous links of these routes. This confirms the need to develop and test new mathematical models to solve these problems.

Formulation of research objectives (problem statement). The purpose of the work is to develop a mathematical model of mixed cargo transportation in conditions of dynamic changes in risks to increase the reliability of the transportation process, analyze alternative options for transportation, and identify opportunities to change the route even in the process of cargo transportation.

Achieving the goal of the research made it necessary to set and solve the following tasks:
- implement the ability to analyze alternative transportation options and propose route changes in real time;
- prove the possibilities of the developed model on the example of specific enterprises;
- to ensure reliability forecasting of the next stages of cargo transportation;
- implement the possibility of optimizing multi-purpose tasks to ensure reliability, minimize the cost and time of transportation;
- carry out a stratification of the reliability of cargo transportation according to the level of risk probability.

Materials and methods. Mathematical formalization of the task of ensuring adequate reliability of transportation due to the variability of the cargo transportation routes stages required the stratification of the reliability of cargo transportation depending on the risks at individual stages. To perform this task, the method of quantitative and qualitative comparison is used. The result of the stratification of cargo transportation reliability is shown in Table 1.
Table 1. Stratification of cargo transportation reliability.

<table>
<thead>
<tr>
<th>Limits of changes in transportation reliability</th>
<th>The level of transportation reliability</th>
<th>Probability of threat</th>
<th>Linguistic assessment of the level of reliability of transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>L≥6.6</td>
<td>L1</td>
<td>ω=10×(0.25−1/L)</td>
<td>Maximum</td>
</tr>
<tr>
<td>6.6&lt;L&lt;4</td>
<td>L1</td>
<td>ω2=10×(0.45−1/L)</td>
<td>High</td>
</tr>
<tr>
<td>4&lt;L&lt;2.86</td>
<td>L2</td>
<td>1−ω2=ω2</td>
<td>High</td>
</tr>
<tr>
<td>2.86&lt;L&lt;0.45</td>
<td>L2</td>
<td>ω2=10×(0.65−1/L)</td>
<td>Medium</td>
</tr>
<tr>
<td>0.45&lt;L&lt;1.8</td>
<td>L3</td>
<td>L3=1−ω2=ω2</td>
<td>Medium</td>
</tr>
<tr>
<td>1.8&lt;L&lt;1.5</td>
<td>L3</td>
<td>ω3=10×(0.85−1/L)</td>
<td>Small</td>
</tr>
<tr>
<td>1.5&lt;L&lt;1.3</td>
<td>L4</td>
<td>L4=1−ω3=ω4</td>
<td>Small</td>
</tr>
<tr>
<td>1.3&lt;L&lt;1.17</td>
<td>L4</td>
<td>ω4=10×(0.85−1/L)</td>
<td>Minimal</td>
</tr>
<tr>
<td>1.17≤L</td>
<td>L5</td>
<td>L5=1−ω4=ω5</td>
<td>Minimal</td>
</tr>
</tbody>
</table>

Source: own development.

Taking into account the probability of the risk of cargo transportation at each stage of mixed transportation is carried out in accordance with the methodology Kotenko, 2022 using a matrix of vectors:

\[
\vec{\omega} := f(\vec{P}, \vec{e})
\]

where \(\vec{\omega}\) - vector of risks, which according to the theory of vector analysis can be represented as a matrix; \(\vec{P}\) - probability vector of each of the risk factors; \(\vec{e}\) - vector of risk consequences for each of its factors.

Using the method of induction and deduction, we consider the reliability of transportation as the inverse of the risk of transportation, i.e.

\[
\vec{L} = \vec{\omega}^{-1}
\]

where \(\vec{L}\) – transportation reliability vector.

This approach allows you to fragment the process of mixed transportation and consider the transportation problem as a time-distributed set of vectors. The fragmentation method of the problem allows to include probable stages of transportation in different transport routes. That is, when the cargo is already on the way due to an excessive increase in the level of risks at some subsequent stages of the transportation route, there is an opportunity to transport the cargo by another route, alternative to the risky one but with a higher level of reliability.

From the point of view of transportation organization and risk management, this requires a different approach than the existing ones to the formation of desired cargo transportation routes. In the period preceding the war, the formation of logistics routes was based on the principle of choosing a short logistics arm, which almost automatically ensured the minimization of the cost and time of transportation. With a significant probability of risks, ensuring the reliability of transportation becomes an urgent task. Therefore, the more fragmented the transportation route becomes with the formation of the changing possibility of the transportation path after each of its stages, the more opportunities there are for implementing the proposed reliability assurance tool.

Under the conditions of the staged implementation of the mathematical formalization method of the problem after choosing the route, this requires the use of a Kalman filter for recursive checking of all parameters affecting transportation along the selected route, including transportation risks. The use of the Kalman filter is also due to the fact that it allows the use of uncertain parameters. This is especially important given the variability of the situation during the war. The Bayesian method is chosen as the basic method when using the Kalman filter. This is due to the fact that this method takes into account the relationships between the risks of various stages of the cargo transportation route and allows for successive calculations for each of the stages. This provides the possibility of their variable use in different transportation routes. In general, for the implementation of the method of mathematical formalization, the approach of Bazaluk, 2021 was used, which allows to assess not only the impact of risk on the reliability of the transportation of goods...
by water transport, but also to estimate the cost and
time of transportation for each of its stages. This
makes it possible to effectively optimize the
transport process at the same time according to
several target functions: reliability, cost and time
of transportation.

It is proposed to present the mathematical
formalization of the problem in the following
form:

\[
\begin{align*}
\frac{d\tilde{b}}{d\tau} &= \gamma(\tilde{z}, \tilde{L}) + f(\tilde{z}, \tilde{L})\tilde{u}(\tau) \\
\frac{d\tilde{u}}{d\tau} &= \varphi(\tilde{z}, \tilde{L}) \\
\tilde{g}(\tau) &= U(\tilde{u}, \tilde{z})
\end{align*}
\]  

(3)

where \(\frac{d\tilde{b}}{d\tau}\) – the derivative of the domain of
parameters in time \(\tau\) when the condition \(\tilde{z}, \tilde{u} \in B\) is
fulfilled; \(\tilde{z}\) – a vector of transport parameters under
condition fulfillment \(\tilde{z} \notin \tilde{g}, \tilde{u}\); \(\tilde{u}(\tau)\) – vector
of possible next stages of transportation for changing
the route in time \(\tau\) under condition fulfillment
\(\tau \in [\tau_i \ldots \tau_{i+1}]\), \(\tilde{v}_i\) – start time of \((i)\)-th stage
of transportation; \(\tau_{i+1}\) – end time \((i + 1)\)-th stage
of transportation; \(\frac{d\tilde{u}}{d\tau}\) – rate of change of the risk
vector over time; \(\tilde{g}(\tau) \in B\) – vector of parameters
of adjacent types of transport on possible
transportation routes; \(\tilde{u} \in B\) – vector of undefined
parameters.

The functionality of this algorithm is also
determined by the possibility of using fuzzy,
stochastic and uncertain variables in calculations.
For this, the entire array of parameters is divided
into arrays of parameters according to the
measurement scale. Further, at each stage of the
transportation route, all existing risks are
determined. At the next stage of the algorithm, the
values of these risks are predicted for the longest
acceptable time of cargo transportation.

For this, the rate of change of the risk vector
\(\frac{d\tilde{u}}{d\tau}\) is calculated, integrate the found magnitude and
find the predictive value of the risk \(\tilde{u}_{i+1}\) at each
moment \(\tau_{i+1}\):

\[
\tilde{u}_{i+1} = \int_{\tau_i}^{\tau_{i+1}} \frac{d\tilde{u}}{d\tau} d\tau - \tilde{u}_i
\]  

(4)

Minimization of time and cost of transportation is
carried out under conditions:

\[
\begin{align*}
\tau_i &\in [\tau_i, \tau_{i+1}] \\
\sum_{i=1}^{\infty} \tau_i &\leq \tau_{\text{max}} \\
c_i &\leq c_{\text{max}} \\
L &\rightarrow L_{\text{opt}} \\
b_j &\in B
\end{align*}
\]  

(5)

where \(\tau_{\text{max}}\) – the maximum acceptable time of
cargo transportation; \(c_i\) – the cost of freight
transportation on the \(i\)-th stage of the route; \(c_{\text{max}}\)
the highest possible cost of transportation; \(L\) -
reliability of transportation; \(B\) – the entire
parameter array; \(b_j\) – parameter arrays by
measurement scale.

At the next stage of the algorithm, a method
based on the theory of fractals is used. It consists
in the fact that for enterprises in a certain region,
transport route options are considered as
randomized fractals, which are selected using the
recursion method. That is, at each stage of the
route, a random parameter is introduced, which
determines the reliability of transportation at the
following stages. For this, an assessment of the rate
of risks change is carried out \(\frac{d\tilde{u}}{d\tau}\), which opens up
the possibility of predicting the transportation
reliability at further stages of logistics routes.

In this way, the dangerous level of transportation at its subsequent stages is detected
in advance, other alternative routes for the further
transportation of goods are selected, and the level
of threat is checked for them (see Table 1). From
the safer options of transportation, the option with
an acceptable level of time and transportation cost
is selected by a sorting method. Next is the value
of integral reliability of cargo transportation along
the entire transportation route.

The analysis confirmed a significant
simplification and, accordingly, a reduction in
calculation time using the developed algorithm.

**An outline of the main results and their justification.** The proposed algorithm was tested
for the optimization of cargo transportation on the
example of oil enterprises in the east of the
country. Due to the significant volume of exports
in 2019, the export possibilities of transporting the
company's products through the ports of the Sea of
Azov were limited due to a significant increase in
the risk of vessel delays when passing through the
Kerch Strait - the level of integral risk along this
route varied from \(L_3\) to \(L_5\) (Kotenko, 2022). For
the transportation of products in some areas, for
example, the Kherson and Mykolaiv regions, rail
transportation of goods for enterprises was one of
the options for the implementation of the transport
process, but with a higher level of risk than for
transportation by water transport in water areas
that were not threatened by the aggressor.
Therefore, options for the use of river vessels and
"river-sea" type vessels were considered to offer
transportation options alternative to rail
transportation. Reliability of cargo transportation by
rail was assessed by: risks of accidents and
incidents due to outdated railway infrastructure,
significant delays during transshipment at railway and sorting stations, loss and damage of cargo, etc. Such similarity of logistics problems for enterprises of the region contributed to their use of the fractal method. For its application, options for transport routes were proposed and, as a result, an increase in the reliability of transportation due to the avoidance of cargo delays. For example, for the Melitopol Oil Extraction Plant (MOEP), this would lead to a decrease in the level of warehouse stocks by 42%. The main threats to mixed transportation were considered: transportation risks; storage risks, cargo processing risks, distribution and sales risks.

The current total logistics costs of enterprises and their share in the cost of production, the share of costs related to the provision of the logistics process from the total volume of costs were analyzed. The risk of reputation loss due to breach of contract terms was not considered. It was also proposed to take into account the rhythm of deliveries, which led to the reduction of warehouse stocks, that is, the minimization of financial resources "frozen" in them, reduction of costs for maintaining loans, reduction of storage costs.

The analysis showed that according to the average annual indicator, 20.8% of MOEP products were exported. The main export deliveries were made through the Mariupol Sea Port. Therefore, logistical losses for export were not taken into account in the calculations. Railway transport was used to transport the main part of the products. For transportation of raw materials - rail and road transport. Transportation by rail transport was risky due to: risks of accidents and incidents due to outdated infrastructure, significant delays during overloading at railway port stations (for example, at Kherson station - up to 65 hours) and sorting stations, loss and damage of cargo at sorting stations, etc. The risk assessment was carried out for cargo with a volume of up to 200 cubic meters. As an option, the use of "river-sea" vessels and river transport was proposed. Consider, as an example, the Melitopol-Kyiv route. This route was chosen because it clearly demonstrates the feasibility of considering supply reliability to reduce warehousing costs. The importance of this approach is indicated by Table 2, according to which the total costs of MOEP for warehousing and inventory management (27% - items 2 and 4 of Table 2), which are a compensator for transportation risks, are commensurate with transportation costs (30%).

### Table 2. The structure of the main logistics costs

| № / № | Types of logistics activities | Share in the structure of logistics costs, % | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | provision | technological processes | sale | return | In total |
| 1 | Supply of raw materials | 1.77 | – | – | – | 1.77 |
| 2 | Warehousing | 4.87 | 2.66 | 8.97 | 4.31 | 20.81 |
| 3 | Transportation | 7.90 | 4.71 | 16.03 | 1.47 | 30.11 |
| 4 | Inventory management | 1.64 | 0.69 | 3.02 | 0.83 | 6.18 |
| 5 | Freight processing | 2.13 | 3.16 | 4.44 | 2.11 | 11.84 |

Source: YouControl is a complete dossier on every company in Ukraine. As an example, we will also provide an analysis for the Pologiv OEP (POEP). POEP in 2018-2020 (see Table 3) was one of the leaders of companies producing and exporting oil and meal (export market share - up to 16%), so the effective formation of transportation routes was, in this case, quite significant.

### Table 3. POEP production volumes in 2020

<table>
<thead>
<tr>
<th>Product</th>
<th>Produced, quantity, tone</th>
<th>Produced, cost, million UAH</th>
<th>Sold, quantity, ton</th>
<th>Sold, cost, million UAH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sunflower meal</td>
<td>112 214</td>
<td>617.65</td>
<td>105 449</td>
</tr>
<tr>
<td>Unrefined sunflower oil</td>
<td>94 357</td>
<td>1980</td>
<td>102 034</td>
<td>2270</td>
</tr>
<tr>
<td>Soybean meal</td>
<td>25 235</td>
<td>284.38</td>
<td>22 230</td>
<td>242.47</td>
</tr>
<tr>
<td>Refined sunflower oil</td>
<td>19 393</td>
<td>411.87</td>
<td>12 815</td>
<td>278.23</td>
</tr>
<tr>
<td>Soybean oil is unrefined</td>
<td>6 564</td>
<td>121.79</td>
<td>5 740</td>
<td>116.85</td>
</tr>
</tbody>
</table>

Source: The official website of the Pologiv oil extraction plant
For POEP, the possibility of using (according to the data of 2020-2021) river-sea vessels for the transportation of products to the Southwest of Odesa region - the port of Reni and the regions of neighboring countries in the lower Danube, in comparison with the option of using railway route: Pology-Zaporizhzhia-Kyiv-Izmail. For the use of water transport: the stage of transportation of Pologa-Zaporizhzhia and, by "river-sea" vessels, Zaporizhzhia-Reni. Options for the use of both rail and road transport on the Pologa-Zaporizhzhia stage were considered.

At the stage of searching for the system of equations for \( \frac{d\omega}{dt} \) polynomials of the seventh order were used. Their coefficients \( a_1 - a_7 \) given in Table 4.

<table>
<thead>
<tr>
<th>Type of transport</th>
<th>Polynomial coefficients</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a_1 )</td>
<td>( a_2 )</td>
</tr>
<tr>
<td>Railway</td>
<td>420</td>
<td>0.05</td>
</tr>
<tr>
<td>River</td>
<td>547</td>
<td>10.21</td>
</tr>
<tr>
<td>Automobile (Melitopol-Kherson)</td>
<td>1258</td>
<td>5.7897E-2</td>
</tr>
</tbody>
</table>

* taking into account the delay time at railway stations

Source: own development

The calculation results are shown in Table 4. The use of road transport on the Pologa-Zaporizhzhia stage became expedient if the reliability of transportation with the existing delay of cargo in the case of rail transportation reaches the lower limit of the level \( L_3 \).

The replacement of railway transport by river transport was able to provide (see Table 4): a reduction in transportation costs by 38.13% when using rail transport on the Pologa-Zaporizhzhia stage and by 11.7% when using road transport on the Pologa-Zaporizhzhia stage. That is, when using river transport instead of railway, it was profitable even to use road transport, which made it possible to reduce the time of transportation by 1.2 hours and increase the reliability of transportation.

Conclusions and perspectives of further research. The presented work is a continuation of the study (Kotenko, 2022), which provides calculations of the reliability of cargo transportation through the ports of the Sea of Azov in 2018-2022 before the start of large-scale military operations.

The results of the research carried out by the authors allow us to draw the following conclusions:

1. A mathematical model was developed to increase the reliability of mixed cargo transportation in conditions of dynamic changes in risks, which is especially important for cargo transportation in wartime conditions.

2. The use of the model provides an opportunity to optimize transportation according to the main objective function of the reliability of cargo transportation and the objective functions of the second order - the cost and time of transportation.

3. The model is easy to use and provides opportunities for practical application in real time.

4. The use of the model ensures the analysis of alternative transportation options and provides an opportunity to offer more reliable route options.

5. Using the model, the activities of enterprises that transported their products through the ports of the Sea of Azov were analyzed. Due to the decrease in the reliability of cargo transportation through the Kerch Strait, alternative routes for the transportation of mixed cargo were proposed, for the use of "river-sea" vessels at certain stages.

6. The use of the developed mathematical model for analyzing the activities of enterprises indicated the clear and implicit advantages of increasing the level of transportation reliability, in particular, regarding the identification of the possibility of reducing warehouse stocks with a significant saving of working capital at the same time.

The presented results of the study indicate the possibility of ensuring adequate reliability of transportation of mixed cargoes, even in conditions of significant dynamic changes in the level of threats on transportation routes.

The prospect of prolonging the research of this problem is the development of an automated information system capable of collecting, evaluating and using information about the entire set of parameters regarding the main chosen route of cargo transportation and alternative options.
REFERENCES


The official website of the Pologiv oil extraction plant. Available online: https://mezpology.zp.ua/ (accessed on 2 November 2022).


