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THE USAGE OF GENETIC ALGORITHMS WHEN PLANNING RAILWAY TRANSPORTATION IN INTERNATIONAL CONNECTION

Summary. *The railway transport system in Ukraine stands as a pivotal sector within the nation's transportation infrastructure, accounting for a substantial portion of freight and passenger movement compared to domestic alternative modes of transportation. With direct border connections and collaboration with railways in Moldova, Poland, Romania, Slovakia, and Hungary, Ukrzaliznytsia JSC facilitate operations through forty international railway crossings. The political climate in Ukraine, particularly the focus on export to EU countries, has sparked increased interest in transportation towards western border regions [1, 2]. This article delves into the challenges and opportunities surrounding the enhanced cooperation of Ukrainian border terminals with EU countries during wartime and post-war periods. It analyzes the current state of freight transportation to Europe, addressing existing challenges and outlining short- and long-term development prospects for railways. Emphasis is made on the vital role of railway transport in Ukraine's integration into the European transport network, presenting avenues for implementing plans connected with railway reconstruction and development. Container transportation commands a significant market share, with a growing trend towards its adoption. Container transport facilitates a substantial reduction in loading operations, a notable increase in labor productivity, and enables comprehensive mechanization and automation of cross-docking operations. As a transit country, four out of ten existing pan-European transport corridors traverse Ukraine, the nation possesses considerable potential for developing its railway transport system. With the third-largest railway network in Europe (19.787 km, including 9.319 km of electrified tracks), railway transport assumes a leading role in Ukraine's transportation landscape. However, despite its advantages, Ukraine's transportation and logistics system lags behind those of other countries worldwide. Modernization of tracks and rolling stock necessitates significant capital investment and time, underscoring the immediate need to enhance the quality of logistics services [3]. Therefore, this article explores optimization methods for container traffic from Ukraine to EU countries with the use of mathematical methods and algorithms. The genetic algorithm among the discussed methods is recognized as one of the premier mathematical algorithms for the specified task. This approach could play a pivotal role in establishing a robust technical system for railways along Ukraine's western border, optimizing border crossing operations, and enhancing Ukrainian railway transportation capabilities. It not only aids in identifying the fastest or most economical routes but reveals weaknesses in Ukrainian border terminals. Additional strategies can be devised for modernizing and expanding border terminals and stations by leveraging this insight, facilitating the integration of Ukrainian railways into the European transport system.*

Key words: *railway infrastructure, freight transportation, container transportation, genetic algorithms, optimal route, export, logistics, international transportation, material-technical support, border terminals.*

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1. INTRODUCTION

The railway transportation sector constitutes a significant portion of Ukraine's economy and remains the leading mode for transporting goods of all kinds. Despite its potential for rapid development, Ukrzaliznytsia JSC find themselves in a vulnerable position. A full-scale war which began in 2022 have made railway exports to the eastern part of the country and through the ports of the Black and Azov Seas practically impossible. In 2024, ongoing hostilities within Ukrainian territory continue to be the main obstacle to the development of railways and the logistical network. However, the military conflict may positively impact the image of railway transportation. Ports are not operating at capacity, and air transport is temporarily unavailable, thereby enhancing the competitiveness of other modes of transportation, including railways. Moreover, Ukraine has shifted its focus towards strengthening relations with EU countries. It includes increased exports to the European Union market. This trend creates prerequisites for investing in the country's reconstruction and modernizing existing infrastructure. Since Ukrainian railway transport stands to benefit from potential modernization, it is pertinent to address the issues Ukrzaliznytsia JSC is facing and explore ways to resolve them.

2. PROBLEM STATEMENT

Despite the challenging situation in Ukraine's transportation logistics, container transportation by rail showed a positive growth trend in 2023. The blockade of ports redirected freight flows from cargo ships to railway border crossings in the west of Ukraine. This trend requires Ukrainian carriers to meet European standards and modernize border terminals. As of 2024, railway stations already face problems with long queues and wagon downtimes. Consequently, delivery times increase and the quality of transportation services is affected. Therefore, it is necessary to find new logistic solutions for the rational distribution of wagon traffic.

3. RESEARCH RELEVANCE

According to data provided by Ukrzaliznytsia JSC, container transportation increased by 34 % in 2023, reaching 201.2 thousand TEUs (only considering loaded containers, excluding empties). It is approximately equivalent to the volume in 2019. Out of these 201.2 thousand TEUs, 62 % of containers were exported, 19 % were imported, and another 19 % were transported within Ukraine. Another market leader, Laude, notes that the company has begun to restore volumes over the past year. According to Laude, 104.3 thousand TEUs were transported in 2021, 61.2 thousand TEUs in 2022, and 89.3 thousand TEUs in 2023. A positive trend is also reported by N'UNIT Company, with transport volumes doubling in 2023 compared to 2022 and approaching pre-war levels.

Overall, railway container transportation demonstrates solid growth. In September 2024, Ukrzaliznytsia JSC plans to introduce new container routes related to transportation from Ukraine to European countries. This trend of increasing container volumes will continue, which justifies the relevance of the chosen topic [4].

4. FORMULATION OF THE PURPOSE AND OBJECTIVES OF THE ARTICLE

The purpose of this research is to enhance the planning processes of railway transportation in international connections. This can be achieved by identifying methods to redistribute wagon traffic at Ukrainian border terminals. The defined task entails the usage of optimization mathematical models and algorithms [5]. In our study, we will use a genetic algorithm since it is widespread and effective in the railway transportation logistics of Ukraine [6, 7].

5. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The interest in the development of container transportation by transporters continues to increase [8, 9]. It is related to the features and advantages which container transportation offers compared to conventional transportation methods [10–13]. It is crucial to consider the current political situation and processes occurring at border terminals while Ukraine is at war [14].

6. PRESENTATION OF THE MAIN MATERIAL

As mentioned above, container transportation is increasingly dominating Ukraine's transport market. Freight volumes in containers in 2023 were 34 % higher than in 2022 when only 150 thousand TEUs were transported. Previously, in 2021, Ukrzaliznytsia JSC transported 279.8 thousand TEUs.

Considering cargo types, grains accounted for the largest share of containerized cargo in 2023 – 49 %, followed by ferrous metals – 17 %, meal – 14 % and oil – 10 %. Export cargo transportation in containers in 2023 amounted to 124,946 TEUs, imports – 37,083 TEUs, domestic – 38,387 TEUs, and transit – 844 TEUs. However, despite the improvement in transportation volume indicators, the state of border terminals can and should be improved.

The first problem logistics companies faced was the reorientation to not typical for rail container transportation goods. Grain and oilseed crops remain the primary commodities for container transportation [15].

The statistics on train/wagon turnover through the border crossings of Ukrzaliznytsia JSC regional branches as of January 28, 2024, indicate that on the Ukraine-Poland route, the daily wagon turnover is 831 wagons across four crossings. Out of these 831 wagons, 174 are designated for grain crops. This trend in grain cargo is only growing. Over the week at the Yagodyn – Dorohusk crossing, there was an increase in the average daily transfer of grains by +5.03 wagons per day, or +11.33 %. Similarly, at the Mostyska II – Medyka crossing, there was an increase of +1.08 wagons per day (+4.56 %). Overall, 92.46 wagons with grain are transferred daily through Polish crossings, and this indicator increased by +3.79 wagons per day or +4.27 % per week. It brings us to the problem of wagon queues at terminals. Since there is a redirection to railway transportation and the presence of goods towards border crossings will continue to grow, this will inevitably lead to an increase in queues at border crossings. As of January 28, 2024, the total available cargo is measured in the amount of 4958 wagons, of which 2619 are grain crops and plant-based products (grain, oil, meal, pellets). According to Ukrzaliznytsia JSC, the indicators of queue downtime at border crossings with the average daily turnover are summarized in Table 1.

Table 1

The number of wagons in the queue at railway crossings [16]

No.	Border crossing/junction	The presence of cargo in the direction of the border crossing as of January 28, 2024 (wagons)	Queue at the border crossing with average daily turnover (in days)
1	Yagodyn-Dorohusk	390	2
2	Izov-Grubeshuv	3856	10
3	Rava-Ruska-Verkhovyna	32	3
4	Mostyska-2-Medyka	680	3

Based on the data from the table, wagon downtime at the crossings with Poland ranges from 2 to 3 days. However, as observed at the Izov-Grubeshuv crossing, Ukrainian terminals require modernization to mitigate substantial queues as wagon traffic increases at the station.

A redistribution of freight traffic from the most congested terminals to others is proposed via route optimization based on provided statistical data. The scope of application of mathematical models and approaches is constantly expanding in transport logistics. Finding optimal routes for transport vehicles is a task that is easy to formulate but sometimes challenging to solve.

Algorithms designed to find optimal routes can be divided into two groups: precise and heuristic (imprecise) methods.

Precise methods: the characteristic feature of these methods is the guarantee of finding optimal solutions with high overall process complexity. Therefore, precise methods are applied when dealing with relatively simple tasks that do not contain a large amount of data to process. Despite this, they find wide application in optimization processes in the transport, industrial production, and material management sectors.

Heuristic (inexact) methods are often used to compensate for the limitations of exact methods. One of the main advantages is their fast execution time compared to precise methods. It is possible because they do not even use the data unsuitable for calculations. This approach finds wide use for large-scale optimization tasks.

Genetic Algorithm (GA): it mirrors the process of natural selection, where the best individuals are selected for the reproduction of the next generations. A notable feature of GA is the emphasis on using the "crossover" operator, which performs the recombination operation of candidate solutions, analogous to the role of crossover in nature. Alongside the ant colony algorithm, GA are considered the most effective and widely applied in practice. They guarantee a solution close to the optimum in a relatively short time.

Numerous programs have been developed to solve this problem based on specific algorithms, methods, and mathematical models. One of the leaders in this field is GA; this software product allows for reducing the time required to find the most advantageous transport option and avoiding additional costs. It has proven well and is widely used even beyond the transportation industry. Since the algorithm is quite flexible and can handle large volumes of data, its usage is proposed.

Advantages and Disadvantages of the GA are given below:

– Advantages:
    1. GA operate with codes, representing a formalized set of parameters. Manipulations with codes occur independently of their content during the operation of the GA, meaning the code is considered a string of bits.
    2. It is one of the fastest algorithms for finding the optimal solution. It does not use additional information in its work and operates with data in the area of admissible parameter values.
    3. During the search process, GA simultaneously process several points of the search space rather than moving sequentially from point to point, as in traditional methods.
    4. Utilization of two solution mechanisms: deterministic and probabilistic. It allows for obtaining more efficient results than using only one of these mechanisms.
    5. Capable of handling large volumes of data.
– Disadvantages:
    1. Does not always guarantee the optimal solution. Sometimes, this method requires a second attempt to find the optimum.
    2. Complex to implement. Only a professional in genetic programming can implement inherently complex projects.
    3. Lack of diversity in individuals. There is a rapid emergence of a single genotype in the population, representing the maximum local value, and all other individuals prove to be insufficiently competitive in selection. As a result, copies of this individual spread throughout the entire population. Although methods to address this issue already exist.

Mathematical Model Based on GA. It is advisable to consider and utilize multiple criteria to obtain the final result. Allocating n-amount of data arrays, one for each criterion, is necessary. Transport logistics deal with delivery deadlines, security, and transportation costs. Several best options should be proposed to prioritize the most important criterion, but the final decision remains with the human. Calculations must be conducted separately to avoid competition between the data of the objective function.

The objective function describing delivery costs:

$$TC = CV + \sum C_i \to \min, \tag{1}$$

where TC – the total transportation cost; CV – customs value; C_i – the cost price of transportation for the i-th type of transport.

As mentioned earlier, customs expenses are crucial in determining the baseline conditions. Several methods exist for calculating customs expenses, and we are utilizing the value-added method. The assessment of customs value involves calculating various types of expenses and the exporter's profit.

The formula for calculating customs value based on the addition method (CV):

$$CV = CP + CO + EP + BE + LF + PP, \quad (2)$$

where CP – the cost of materials and expenses incurred by the manufacturer in the production of goods; CO – cost of operation in Ukraine; EP – exporter`s profit; BE – buyer`s expenses; LF – license fees for working with intellectual property objects; PP – the portion of profit from the subsequent resale of goods, accumulated by the seller.

The objective function describing delivery time [17]:

$$T_{deliv} = T_t + T_{lod-uld} + T_d + T_b \to \min, \quad (3)$$

where T_t – travel time; $T_{lod-uld}$ – the time spent on loading-unloading operations; T_d – downtime of the wagons; T_b – buffer time.

The stochastic model imposes specific constraints on the objective function. In our scenario, these constraints are defined by user input data. Given that there isn't a set value limiting the cost and transportation time, these values need to be incorporated into the algorithm each time it runs. For instance, the limit on transportation time is set by a human, and the algorithm should adhere to this limit. This approach helps eliminate numerous options that don't comply with the transportation conditions and customer requirements beforehand. The same principle applies to the delivery cost, where transport participants specify the maximum amount within which the search for the optimal solution occurs.

As an example, we analyzed rail transportation from Kharkiv to Berlin (Fig. 1). One of the open-access services, Logistics Explorer, proposes the following route with minimal costs.

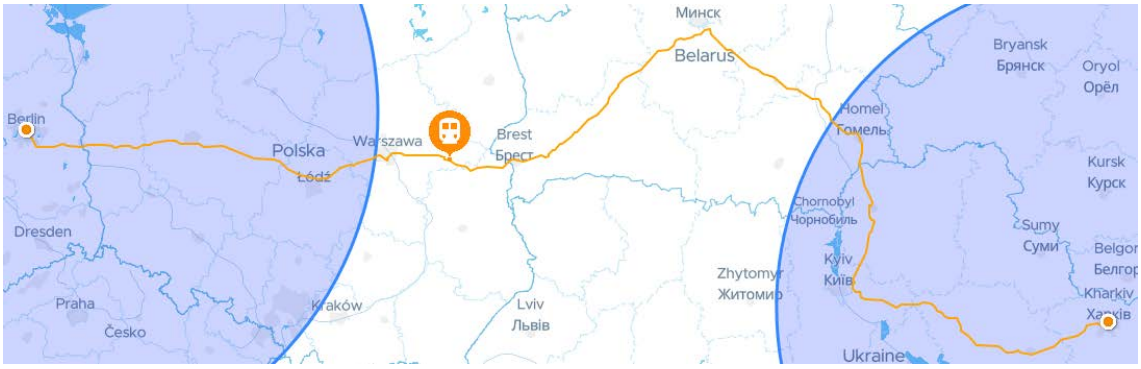

Fig. 1. Transportation option by the Logistics Explorer app

Applying the GA search method, the following route was determined (Fig. 2). The program took approximately 22 seconds to find the optimal route. The total route covers approximately 1941 kilometers, with an estimated duration of about 59.2 hours (excluding downtime at technical stations).

Fig. 2. Transport Route Using the GA Method

The GA presents a more cost-effective and expedient alternative to some existing options. Based on our calculations, the performance indicators of the new transport route by railway from Kharkiv to Berlin better align with the carriers' requirements. The findings are summarized in Table 2.

Table 2

Comparison of the technical and economic indicators

No/	Factors	GA	Current option
1	Average train speed, km/h	16,28	14,42
2	Cargo transit time, hours	119,2	142,9
3	Transportation distance, km	1941	2061
4	Cost of transportation, UAH	124600	132350
5	Economic benefit, UAH	7750	-
6	Annual economic benefit, million UAH	22436	-

7. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The market economy and the increasing international trade volumes incentivize carriers to enhance and streamline transportation planning. Computerization of this process will enable the following.

1. Reduction of time in finding the most efficient solutions, considering criteria such as speed and cost.
2. Decrease the likelihood of errors and the risk of adverse consequences.
3. Integration of legal norms and regulations of countries acting as importers or exporters into calculations.

It is suggested to view the optimization system inherently with the existing automated control systems in railways. This approach facilitates the integration of the proposed method into existing operational management systems. Upon calculating the economic impact of the innovation, the outcome was positive and indicated a payback period of 2 years.

The development of automated systems will positively impact the transportation and logistics industry in Ukraine. Our country has significant opportunities to enhance transportation services and create favorable conditions for improving Ukraine's reputation among foreign clients. The proposed innovation does not necessitate substantial capital investment and can yield positive economic effects by reducing the implementation costs of advanced technologies.

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ВИКОРИСТАННЯ ГЕНЕТИЧНИХ АЛГОРИТМІВ ПРИ ПЛАНУВАННІ ЗАЛІЗНИЧНИХ ПЕРЕВЕЗЕНЬ У МІЖНАРОДНОМУ СПОЛУЧЕННІ

Анотація. *Залізничний транспорт України є провідною галуззю у дорожньо-транспортному комплексі країни, який забезпечує найбільшу частку вантажних та пасажирських перевезень серед здійснюваних усіма видами транспорту на території України. Зазначимо, що українські залізниці безпосередньо межують і співпрацюють із залізницями Молдови, Польщі, Румунії, Словаччини, Угорщини й забезпечують роботу із сорока міжнародними залізничними переходами. Інтерес до перевезень у напрямку західних прикордонних регіонів посилюється тим, що політичне становище країни спонукає переорієнтовуватись саме на експорт до країн ЄС. У статті досліджено виклики та можливості, пов'язані зі зростанням кількості українських прикордонних терміналів із країнами ЄС як у воєнний, так і у післявоєнний періоди. Проаналізовано поточний стан вантажних перевезень до Європи,*

розглянуто нагальні проблеми, а також коротко- та довгострокові перспективи розвитку залізниці. Підкреслено ключову роль залізничного транспорту в сприянні інтеграції України в європейську транспортну мережу, висвітлено можливості для реалізації планів щодо реконструкції та розвитку залізниці. Встановлено, що контейнерні перевезення вже займають значну частку ринку і тенденція до їх використання тільки зростає. Україна, як транзитна держава (через територію України проходять чотири з десяти загальноєвропейських транспортних коридорів), має великий потенціал для розвитку власної залізничної транспортної системи. На практиці контейнерні перевезення дають змогу більш ніж удвічі здешевити операції пакування, збільшити продуктивність праці в 4–5 разів, створити умови для комплексної механізації та автоматизації перевантажувальних операцій. Україна посідає третє місце в Європі (19 787 км залізниць, з яких 9 319 км електрифіковано) за довжиною мережі залізниць, а залізничному транспорту належить провідна роль у транспортній системі країни. Незважаючи на це, транспортно-логістична система України на доволі низькому рівні порівняно з іншими країнами світу. Модернізація шляхів та рухомого складу потребують значних капіталовкладень та часових витрат; отже, на проміжковому етапі загострюється питання пошуку способів покращення якості надання логістичних послуг. Тому в статті досліджено способи оптимізації контейнерного руху з України до країн ЄС за допомогою певних математичних алгоритмів і методів. Одним із описаних методів є генетичний алгоритм, який вважають одним із найкращих математичних алгоритмів для описаного вище завдання. Це може відіграти вирішальну роль у створенні гідної матеріально-технічної системи залізниці на західному кордоні України. Також це могло б сприяти оптимізації пропуску через кордони для реалізації та розширення транспортних можливостей української залізниці. Це не лише допоможе знайти найшвидший чи найдешевший маршрут, але й виявити слабкі місця українських прикордонних терміналів. На основі цієї інформації можна запропонувати більше способів удосконалення для модернізації та розширення прикордонних терміналів і станцій з подальшою інтеграцією в європейську транспортну систему.

Ключові слова: *залізнична інфраструктура; вантажоперевезення; контейнерні перевезення; генетичні алгоритми; оптимальний маршрут; експорт; логістика; міжнародні перевезення; матеріально-технічне забезпечення; прикордонні термінали.*