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Sustainable Development of Intermodal Freight Transportation—Through the Integration of Logistics Flows in Ukraine and Poland

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Abstract: Nowadays, sustainable development is becoming a model for significant improvements in the modern world. Taking into consideration possible future challenges, transport must have sustainable features. Today, such a type of transportation as intermodal transport (transport that uses more than one mode of transportation) is gaining relevance. It is one of the most promising types of transport from an economic and environmental point of view. In this paper, the importance of sustainable development of intermodal freight transport is analyzed; the state of foreign trade and the trade balance in Ukraine and Poland are examined; and the sustainable development trends and prospects of trade relations between two countries are determined, taking into account the existing product structure. It is noted that the post-war recovery of Ukraine will require the activation of logistical flows with EU countries. The analysis of the state of freight transport by various modes of transport allowed for theoretically justifying the insufficient attention given to the development of intermodal freight transport between Ukraine and Poland for logistics optimization in international trade. From a methodological perspective, it is proposed to describe the subject area in terms of graph theory. The practical contribution involved the testing of the proposed model of intermodal freight transport to optimize logistics flows in international trade between Ukraine and Poland, considering the minimization of transport service costs and time. This required refining the mathematical apparatus based on the method of successive moves and linking their development to specific supply chains.

Keywords: foreign trade; trade balance; sustainable development; net exports; intermodal freight transportation; transport logistics; intermodal terminals; logistics flow optimization model

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1. Introduction

These days, it is increasingly apparent that the world's existing transportation systems suffer from serious difficulties, so they do not conduct sustainable development. Countries around the world recognize the central role that transport plays in economic development and are eager to meet the growing demand for mobility under conditions of globalization. The current state of national economies is becoming increasingly integrated into the global system of resources and markets. Their market relationships have become steadily more interconnected due to global supply flows. The rate of economic interaction, with the help of international trade, has grown progressively, causing a growth in the size of the world.

Freight transport is considered a crucial component of welfare generation. It accelerates the movement of goods throughout a supply chain and directly influences the efficiency of the whole economy.

The expected intensification of economic relations between Ukraine and Poland in the post-war recovery period requires the integration of logistic flows between the two countries. The optimization of cargo deliveries from suppliers to consumers should occur in the shortest time and with minimal transportation costs. Modern practical experience

in addressing this issue in international trade stems from the development of intermodal freight transport.

Intermodal freight transport is a transport system involving the transportation of goods when at least two means of transport are used. This means that two or more different transport modes are involved without changing load units during the time of transportation [1–3]. From a scientific standpoint, this direction is also represented by a wide range of research. However, the problem of using economic-mathematical apparatus and modern information technologies to automate the processes of making relevant decisions remains relevant and timely today.

The theoretical, methodological, and practical aspects of the state policy of the transport industry's sustainable development in Ukraine were studied thoroughly by many scientists [1–6]. International cooperation and integration into the international transport system are considered important components according to the definition of regulatory mechanisms and directions for improving its integrity.

As for intermodal freight transport in the international transport logistics system, this scientific direction has been explored in the works of many scientists as well [7–11]. Among the main issues, they highlighted the lack of proper legislative support and the current state of logistic infrastructure in Ukraine. Huge attention should be applied to the improvement of this infrastructure due to the ecological-economic development of Ukraine under the conditions of integration into the EU. It is emphasized that sustainable development is characterized by dynamism, expressed by changes in processes in economic, social, and ecological systems. Under such conditions, the stability of development is based on innovative achievements, with key elements being a decent standard of living and ecological safety in accordance with the needs of the present and the future [12–15].

The creation of an intermodal transport system is advisable to implement based on cargo transport and distribution complexes and terminal complexes, which are built at the intersection of different types of transport. Therefore, significant attention should be paid to the study of the operating conditions of terminal complexes and to exploring intermodal problems of cargo transportation from the point of view of system and management using the proposed model of intermodal cargo transport networks. The corresponding model takes into account the time intervals of container arrival at the terminal [16–18].

The study of the operating conditions of intermodal transportation based on the analysis of costs, taking into account technical and operational parameters, is considered in the work [18]. The model describes the conditions of cargo transportation, taking into account costs at all stages of the transport process.

A detailed analysis of the application of simulation models in the development of terminal complexes is presented in [19], and modeling of terminal operation is carried out in interaction with different types of transport. However, in the respective study, the working conditions of intermodal terminals were not taken into account, considering the vehicles that currently perform cargo handling functions.

The authors devoted considerable attention to solving problems associated with the operation of intermodal cargo transportation based on the routing of flows [20,21]. The studies propose optimization models of intermodal networks to study the competitiveness of alternative routes for the movement of goods.

In the studies [22,23], the state of mixed cargo transportation is considered depending on the conditions and specifics of transportation, and a legal analysis of the concept of "transportation of goods in direct mixed traffic" is provided.

The prospects of sustainable transport development in Europe are associated with stimulating mixed (intermodal) transportation. Therefore, in Europe, the features of the functioning of the intermodal freight transportation system are considered in more detail from the point of view of the behavior of transport organizers and the characteristics of the cargo delivery process [24]. Therefore, addressing issues related to the operation of intermodal terminals, namely the synchronization of processes in cargo operations, which are essential for the formation of mixed transport, is relevant.

The comparison of experiences between Poland and Ukraine, as well as the search for directions for cooperation in intermodal transportation between the two countries, was conducted by the Polish researcher Zbigniew B. [25]. The main problematic aspects of such integration, as he sees them, include not only the absence of the necessary network of transport and logistics centers in Ukraine but also the lack of a multimodal operators' institute as such. Because of this, Polish freight forwarders are not ready to take on high risks in international communication.

Comparing the experience between Poland and Ukraine, attention is drawn to the low specific weight of intermodal transport in the national economy of Poland. Factors affecting its development are explored in works [26–31] by Polish scientists. Outsourcing of logistic services is considered an inevitable stage in the development of the country's transport industry, which positively affects not only international trade but also the domestic market. The authors attribute poor railway infrastructure, a lack of specialized rolling stock, and unevenly distributed terminals as the main restraining factors. As a result, railway transport is unattractive for multimodal operators, and the dominant role continues to be held by road transport.

Considerable attention from Ukrainian scientists is devoted to issues related to the use of economic-mathematical methods and models in the transport industry [3,4]. In their works, tasks of network modeling of transportation processes, set-theoretic approaches, and scenario modeling of freight delivery chain structures were considered.

The theoretical foundations of mathematical modeling of transportation flows were explored through examples such as managing transportation-logistic processes of enterprises, modeling queuing systems of automobile transport at cargo terminals, optimizing passenger transport routes, and more.

Traditionally, transport logistics tasks are solved within the frameworks of special theories that have efficient algorithms for solving various classes of such problems. Graph theory is the methodological basis for solving problems related to minimizing the transport network, finding the shortest path, or maximizing flow. The practical application areas of graph theory as the main tool for describing and modeling various network structures, including transport, water supply, energy, and Internet networks, have been extensively studied. Transport networks are considered elements of economic system stability, directly affecting the performance and risks of supply chains. The other vital factors are optimizing container transport by road, considering criteria such as minimizing distance, costs, and container movements between shippers and receivers [32,33].

Analysis of recent research and publications by Ukrainian and Polish scientists showed that intermodal freight transportation, as a necessary condition for the integration of logistics flows and the development of domestic and international trade in Ukraine and Poland, has significant potential and untapped reserves for further development. However, the economic and mathematical support for this area of transport industry activity requires more detailed coverage and development to this day. As for graph theory, on the one hand, it provides clarity in describing the subject area, and on the other hand, it requires adaptation to specific tasks being solved. In our case, the need to optimize interstate supply routes within intermodal transport requires refinement of the mathematical apparatus.

The purpose of the article is to build a multicriteria optimization model of intermodal freight transportation in terms of graph theory to solve the problem of integrating logistics flows in Ukraine and Poland by determining optimal routes and types of freight transport.

To fulfill this purpose, the following tasks were set and solved:

To conduct a statistical and economic analysis of the current state of international trade between Poland and Ukraine and elucidate their dependence on the specified trade relations.

To investigate the dynamics of freight transport by various types of transport in Poland and Ukraine, taking into account intermodal transport.

To develop an optimization model of intermodal freight transport to minimize the cost of transportation services and time, provide a description of its subject area in terms of graph theory.

This paper is structured as follows: In Section 2, the methodology used in this study is presented. Next, in Section 3, the results of this research are described. In Section 4, the discussion about the results, findings, and implications is presented, followed by conclusions in Section 5.

2. Materials and Methods

The work used the following data from open official sources: the State Statistics Service of Ukraine, transport and international trade statistics [34]; the Central Statistical Office in Poland, transport and communication statistics [35]. The theoretical, methodological, and practical aspects of the state policy for the development of the transport industry in Poland and Ukraine were studied based on current scientific publications [1,2,9,10]. The methodological basis of this study relied on works [3–8,11–15], which are dedicated to network modeling of supply chains and optimization of intermodal container transport.

The statistical and economic analysis of the state of international trade between Poland and Ukraine was carried out using methods of general statistics theory, including absolute and relative indicators of the dynamics of levels of time series, structures, comparisons, and averages. The formulation of the problem of intermodal freight transport was carried out in terms of graph theory. Its mathematical interpretation is presented in the form of a multicriteria integer programming problem and is solved based on optimization by sequential steps.

3. Results

In 2016–2020, the total volume of foreign trade in Ukraine increased from 89.7 billion USD to 103.5 billion USD, or +15.4%. In 2021, the growth accelerated by another +36.1%, and in the annual total, this figure amounted to 140.9 billion USD [36]. It meant the gradual integration of the Ukrainian economy into the international trade system.

However, a comprehensive assessment of these trends is impossible without taking into account the trade balance. A systematic excess of imports over exports may indicate a resource-based economy with a low level of competitiveness. A negative manifestation of a trade balance is the constant pressure on the national currency exchange rate and its depreciation over time. In Ukraine, the outstripping growth of imports over exports began after 2014. Although in 2016, net exports were still positive and amounted to +0.5 billion USD, in 2017, this figure was already −2.5 billion USD. This trend has continued: in 2020, the trade balance was −5.1 billion USD, and in 2021, it was −4.8 billion USD. In our opinion, the main reasons for this phenomenon are the following:

- The temporary occupation of parts of Donetsk and Luhansk regions of Ukraine since 2014, on the one hand, reduced the production of domestic energy resources and required an increase in their imports; on the other hand, it negatively affected the export potential due to the loss of some metallurgical enterprises;
- The creation of a deep and comprehensive free trade area with the EU has exposed all the shortcomings of the Ukrainian economy. Competition has spread not only to foreign but also to domestic markets.

In Poland, in 2016–2022, the fastest growth in foreign trade was observed until 2018 and after 2020. The total increase from 405.7 billion USD to 752.8 billion USD was +85.5% and exceeded the similar dynamics in Ukraine [37]. In addition, in terms of value, Poland was almost five times ahead of Ukraine for this indicator. The trade balance in different years took on both positive and negative values but was generally characterized by a balance of exports and imports.

As for the foreign trade between Ukraine and Poland and the prospects for its development, in 2016 its volume amounted to 4.9 billion USD, in 2020 it increased to 7.4 billion USD, or +51.5%, and in 2021 it increased to 10.2 billion USD, or even +37.4% annually.

Thus, trade relations between two countries developed more dynamically than in Ukraine as a whole.

According to 2021 data, in the structure of foreign trade by geographical indication, Poland held the second place for Ukraine after China, with a share of 7.2%. Moreover, if in 2016, the trade balance with Poland for Ukraine was negative and amounted to −0.5 billion dollars, in 2021, it was already +0.3 billion dollars.

On the other hand, for Poland, trade relations with Ukraine did not exceed 1.5% of its international trade volumes. Therefore, due to a significant economic development lag, Ukraine turned out to be more dependent on the results of this cooperation. To obtain an idea of the volumes of external trade between the two countries by type of product, one can refer to the data in Figure 1.

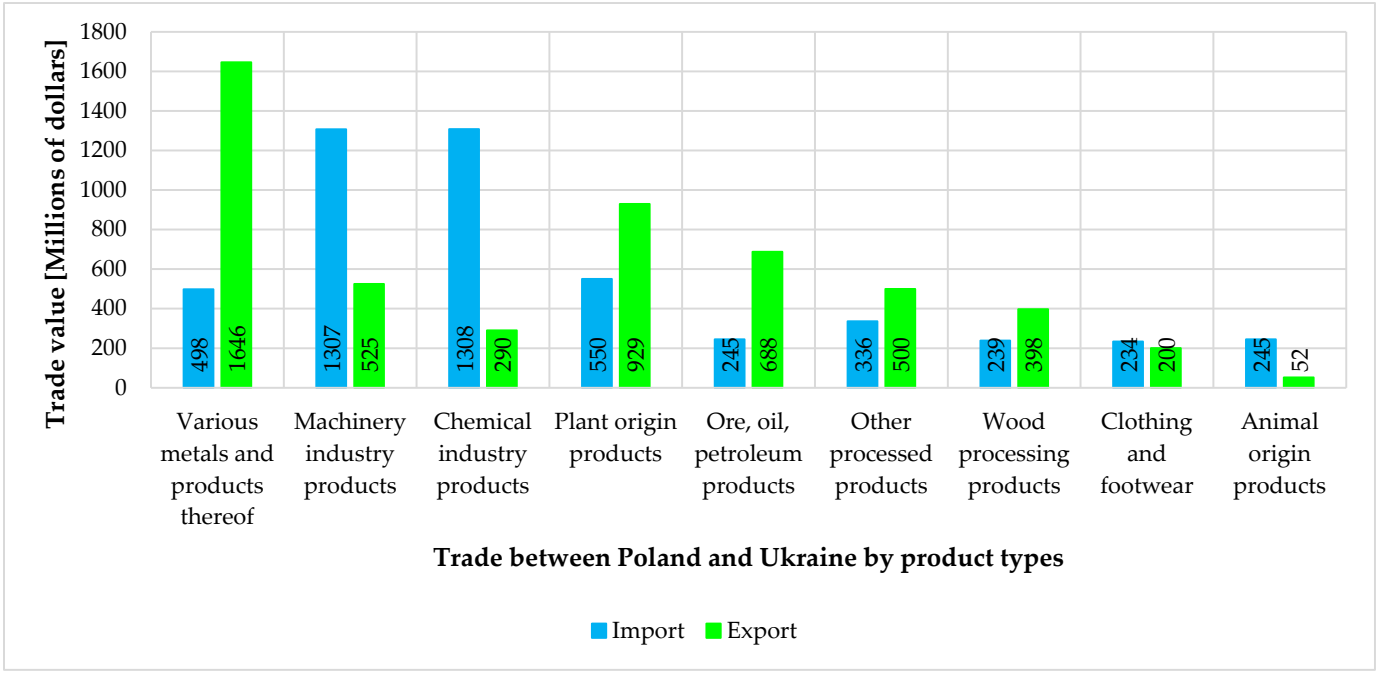

Figure 1. Volumes of Ukraine's external trade with Poland, according to 2021 data, are in million dollars [36,37].

In connection with the principle of comparative advantage, each country supplied the other with the products it could produce at a lower alternative cost. Thus, Ukraine exported the most to Poland various metals and products thereof (1645.7 million dollars), including ferrous metals (1391.3 million dollars); plant products (929.4 million dollars), including fats and oils (395.0 million dollars); and food industry waste (193.7 million dollars); ores, oil, and oil products (687.8 million dollars). Conversely, the main items of exports from Poland to Ukraine were machinery (1307.3 million dollars), including automotive transport (516.7 million dollars), equipment for electrical and thermal power engineering (420.2 million dollars), and electric machines (343.5 million dollars); products of the chemical industry (1308.3 million dollars), namely plastics and polymer materials (449.0 million dollars); and fertilizers (234.3 million dollars).

It can be observed that, to date, Ukraine mainly supplies primary resources to Poland, while in the opposite direction, more technologically advanced products of the processing industry are supplied. Such a structure of trade relations is disadvantageous for Ukraine since the largest share of value-added is created in high-tech production. Therefore, it is necessary to focus on innovative development. The existing dynamics and market volumes allow a positive assessment of the growth potential of international trade between the two countries.

The transport sector of both countries serves the areas of freight and passenger transportation. In our case, scientific interest is focused on the logistics of freight transportation, which is carried out by road, rail, pipeline, river, maritime, and air transport. Their comparative dynamics in Poland and Ukraine based on data from 2016 to 2022 are presented in Table 1, million tons.

Table 1. Comparative dynamics of cargo transportation by various modes of transport in Poland and Ukraine in 2016–2022 (million tons).

Types of Freight Transport	Poland				Ukraine		
	2016	2020	2021	2022	2016	2020	2021
Railroad	222.5	218.4	237.9	237.6	343.3	305.5	314.3
Automobile	1546.6	1919.2	1952.3	1976.3	1085.7	1232.4	224.0
Pipeline	54.1	51.5	49.9	52.6	107.2	97.0	77.6
Other	13.5	12.2	13.3	10.6	7.1	6.0	5.4
Total	1836.7	2201.3	2253.4	2277.1	1543.4	1640.9	621.3

Not including intermediate consumption; Built by the author based on sources [36,37].

The data in Table 1 indicates that Poland and Ukraine share common features in the structure and dynamics of freight transportation, namely:

The highest share in both countries belongs to road transport. In Poland, at the end of the reporting period, it accounted for up to 87%, and in Ukraine, it constituted 75% of the total volume of freight transport in 2021. Changes in the methodology for calculating the volumes of road freight transport occurred in Ukraine in 2021, making these data incomparable with previous years.

The main growth in volumes of freight transport in both countries was provided by road transport. As a result, the overall dynamics of transport services in Poland increased by +24.0% and in Ukraine by +6.3%.

Despite these trends, road transport cannot displace others for several reasons:

The logistical infrastructure of certain industries is oriented towards the use of rail transport, such as the metallurgical complex or port economy.

Large volumes of certain types of goods, based on their physico-chemical properties, are economically feasible to transport by specific means. For example, using the main oil and gas pipeline systems for the long-distance transportation of natural gas and oil.

Water transport, including river and maritime, has the lowest cost and is irreplaceable for international trade and the movement of goods over long distances.

Despite the high cost, air transportation is the fastest means of transporting goods over long distances in cases of urgent needs.

In certain situations, it is impossible to use a single mode of transport from the supplier to the recipient of the cargo due to the existing logistical infrastructure. In such cases, integrating the transport process involves the simultaneous use of several modes of transport. These mixed transports are called intermodal and are a response to the globalization of the economy through international trade. The process of transferring goods from one mode of transport to another is carried out using special intermodal terminals. To facilitate this process, the cargo is transported in standardized intermodal containers [38–41].

Thus, a necessary condition for implementing intermodal freight transportation is the existence of a developed network of specialized intermodal terminals that have simultaneous logistical access to several modes of transport, appropriate production capacities for transshipment, and warehouse areas for storing containers. In Poland, as of 2020, 34 such terminals were in operation, and by 2021, the number had increased to 39 terminals. However, in 2022, only 35 terminals were operational. In Ukraine, as of the end of 2021, there were about 30 such terminals.

4. Discussion

The advantages of intermodal transportation for end-consumers of these services include:

Flexibility and global coverage—the lack of attachment to a specific type of transport means high adaptability to the needs of clients or restrictions in the political and economic environment of certain countries participating in global trade; this opens up opportunities for moving goods around the world on a "door-to-door" basis.

Economic efficiency and environmental friendliness—building logistic routes can pursue various goals: minimize delivery costs or time; reduce the negative impact on the environment. The latter goal can be achieved by using railway or electric road transport. There is also the possibility of solving problems of multi-criteria optimization, taking into account several criteria simultaneously. An additional advantage for cargo owners is the ability to pay for services at a single (through) tariff calculated by the transport operator.

Transportation safety is the movement of goods carried out using standardized containers that provide physical protection to prevent losses or damage. An integral part of this process is cargo insurance.

Use of modern information technologies—the application of information systems and automation technologies at every stage of the logistics process allows for route optimization; real-time cargo tracking, and communication between its various participants.

Centralized accounting of intermodal transportation in Poland is carried out by the Central Statistical Office (Główny Urząd Statystyczny), and the key indicators for 2016–2022 are presented in Table 2.

Table 2. Intermodal transportation volumes in Poland in 2016–2022.

Indicators	2016	2020	2021	2022
Total annual transshipment capacity of intermodal transport terminals [mln. TEU] Including:	8.3	8.2	8.1	8.7
marine terminals [mln. TEU]	5.6	5.2	4.9	4.9
land terminals [mln. TEU]	2.7	3.0	3.2	3.8
Volume of transshipped containerized cargo [mln. tons], including:	48.2	77.9	82.1	84.2
Transported by sea [mln. tons]	21.5	29.2	31.1	29.7
By road [mln. tons]	12.9	25.5	26.4	25.9
By railway [mln. tons]	13.8	23.3	24.6	28.6
Structure of transshipped goods by weight [incl.]				
Unknown goods [%]	–	32.5%	55.0%	62.3%
Mixed goods [%]	23.8%	24.7%	14.4%	11.2%
Foodstuffs [%]	12.5%	11.5%	8.5%	2.9%
Chemical products [%]	7.3%	10.2%	5.1%	5.3%

Built by the author according to sources [37].

The capacity of intermodal transport terminals is measured in TEUs—a unit of cargo equivalent to the volume of a 20-foot container. According to data from 2016, the loading coefficient of transshipment facilities were only 57.6%, including 63.3% at maritime terminals and 45.7% on land. For this reason, in the following years, the volumes of transshipped container cargo increased from 48.2 to 82.1 million tons without an increase in production capacities. The highest share of them, from 37.4% to 44.6%, was occupied by maritime transport. Comparing the data from Tables 1 and 2, it can be concluded that during 2016–2022, the share of intermodal transport in the total volume of cargo increased from 2.6% to 3.7%.

As for Ukraine, the State Statistics Service, summarizing the results of the transport industry, does not conduct a separate account of intermodal freight transportation. However, their development should become the basis for further integration of logistics flows with Poland. Instrumental means for solving this task are economic-mathematical methods and models. In our case, it is appropriate to apply graph theory. Figure 2 schematically

illustrates the logistic networks of two types of freight transport. In the case of international trade between Ukraine and Poland, they will be represented by road and rail connections.

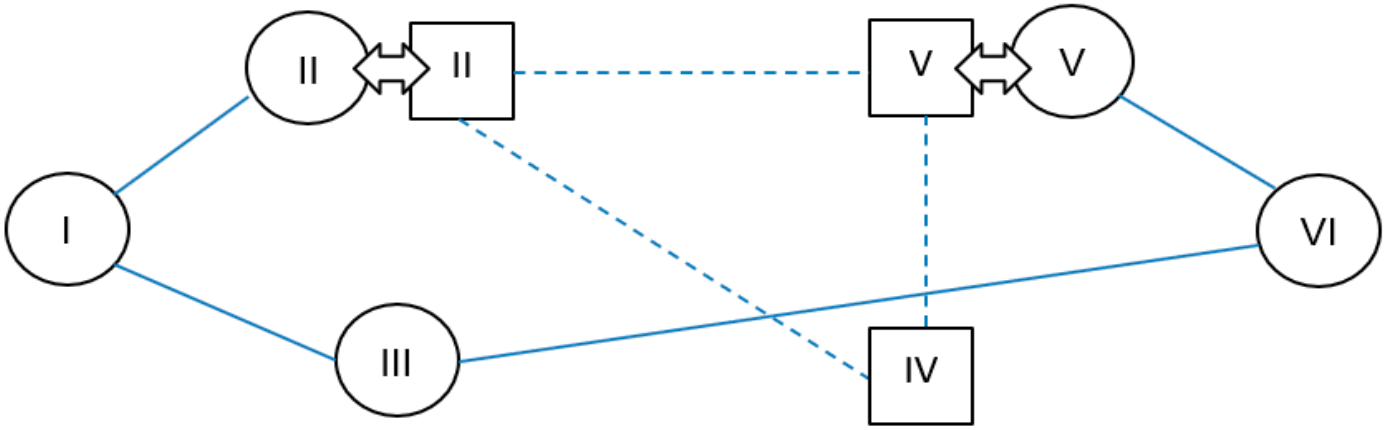

Figure 2. Scheme of intermodal freight transportation in terms of graph theory.

In Figure 2, the following conventional symbols were used:

The vertices of the graph, which have an oval shape and are connected by continuous edges, represent the logistic network of the first type of transport.

The vertices of the graph, which have a square shape and are connected by dashed edges, represent the logistic network of the second type of transport.

Intermodal terminals allow cargo handling and are denoted on the graph by vertices II and V.

Then, from vertex I to vertex VI, the cargo can be delivered by one of the following routes:

Vertex I, vertex III, and vertex IV.

Vertex I, vertex II, transshipment, vertex V, transshipment, and vertex IV.

Vertex I, vertex II, transshipment, vertex IV, vertex V, transshipment, and vertex IV.

Each edge of the graph has corresponding weights: the average cost of transporting 1 TEU and the average time for performing a given operation. These parameters are also relevant for intermodal terminals. Therefore, an optimization problem arises in choosing the optimal route that ensures the fastest cargo transportation with minimal costs.

Now let us introduce the symbolic reference for the intermodal freight transportation optimization model. The cost of processing 1 TEU of cargo (transportation or transshipment) is indicated by matrix S, and the time for performing these operations is indicated by matrix T.

$$S = \begin{bmatrix} s_{11} & s_{12} & \dots & s_{1n} \\ s_{21} & s_{22} & \dots & s_{2n} \\ \dots & \dots & \dots & \dots \\ s_{n1} & s_{n2} & \dots & s_{nn} \end{bmatrix}, \; T = \begin{bmatrix} t_{11} & t_{12} & \dots & t_{1n} \\ t_{21} & t_{22} & \dots & t_{2n} \\ \dots & \dots & \dots & \dots \\ t_{n1} & t_{n2} & \dots & t_{nn} \end{bmatrix}, \tag{1}$$

where s_{ij} and t_{ij} are respectively the cost of handling 1 TEU of cargo and the time of this operation from the i-th node of the graph to the j-th one; n is the number of nodes in the graph.

The variables in the model are the matrix X of the same dimension.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & \dots & x_{nn} \end{bmatrix}, \; X_i = \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix}, \; X_j = \begin{bmatrix} x_1 & x_2 & \dots & x_n \end{bmatrix}, \tag{2}$$

where x_{ij} is a Boolean variable that takes the value $x_{ij} \in [0;1]$ $x_{ij} \in X$.

If x_{ij} = 1, then the work from the i-th to the j-th node of the graph must be performed backwards. In Formula (2), matrix X_i is a column matrix whose elements are equal to the

sums of the corresponding rows of matrix X; X_j is a row matrix whose elements are equal to the sums of the corresponding columns of matrix X, Formula (3). Thus, matrix X_i contains data on the nodes of the graph where the route starts, and matrix X_j contains data on the nodes to which it comes.

$$x_i = \sum_{j=1}^{n} x_{ij},\ x_j = \sum_{i=1}^{n} x_{ij}, \tag{3}$$

The solution of the intermodal freight transportation model involves finding the optimal path from the first node of the graph to the nth. The initial move from the first node provides a Constraint (4), and the final entry to node n is provided by a Constraint (5).

$$x_i = 1\ for\ i = n, \tag{4}$$

$$x_j = 1\ for\ j = n, \tag{5}$$

In addition, the route must be continuous. So, if the route has entered the k-th node of the graph, it must also leave it. This condition is ensured by the fulfillment of Constraint (6).

$$x_i = x_j\ for\ i = j\ \epsilon\ (2; n-1) \tag{6}$$

The defined route must meet the optimization criteria. In our case, it is minimizing the costs and time of transportation of 1 TEU of cargo. The first criterion is determined by the objective Function (7), and the second one—by Function (8).

$$X_1^{opt} = \sum_{i=1}^{n} \sum_{j=1}^{n} s_{ij} x_{ij} \rightarrow min, \tag{7}$$

$$X_2^{opt} = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} x_{ij} \rightarrow min, \tag{8}$$

The optimal cargo transportation plan according to the first (X_1^{opt}) and second (X_2^{opt}) criteria does not necessarily coincide with each other. Therefore, this multicriteria optimization issue in this study is proposed to be solved by the method of successive concessions in Equations (9) and (10).

$$X_1(X) \rightarrow min, \tag{9}$$

$$X_2(X) \geq X_2^{opt} + \delta, \tag{10}$$

where δ—is the permissible amount of concession according to the minimum time criterion.

The parameter δ is determined by an expert on the basis of acceptable concessions in increasing the time of cargo transportation, which can be used to adjust the route and reduce the total cost of the service. The proposed model of intermodal freight transportation (1)–(8) is universal and allows for solving a wide range of problems, taking into Account different types of transport. For example, environmental friendliness or the share of the route covered by electric vehicles can be added as an optimization criterion.

To test this model, we calculated containerized cargo transportation from Khmelnytskyi, Ukraine, to Lublin, Poland. Within this geographical area, intermodal terminals are located in the cities of Ternopil, Lviv, Zamość, and Drzewce. Taking into account the existing network of roads and railways, a corresponding graph was built, on the basis of which the search for possible routes of cargo transportation was carried out. The first two routes involved the use of exclusively road freight transport, while the third route involved the use of intermodal terminals in Ternopil and Drzewce and the movement of goods between these points by railway.

The first route passed through settlements: Khmelnytskyi, Ternopil, Lviv, Zamość, and Lublin. The total length of the roads is 460 km. Taking into account the average driving speed of 60 km/h, the travel time will be about 7.6 h, excluding loading/unloading

time and possible delays at the border. The cost of transportation was assumed to be proportional to the length of the route.

The second route passed through the cities of Khmelnytskyi, Ternopil, Lviv, Przemyśl, Rzeszów, and Lublin. Its total length was 605 km, and the estimated travel time was 10.1 h. As you can see, it yields the first option in terms of target criteria.

The third route of intermodal transportation passed through settlements: Khmelnytsky, Ternopil, transshipment, Lviv, Drzewce, transshipment, and Lublin. The total length of the road was 140 km, or 2.3 h; rail transportation was 675 km, or 7.5 h. The disadvantage is the lack of direct rail connection between the terminals in Lviv and Drzewce; a certain part of the route is not electrified. As a result, the length of the railroad journey doubled, which increased the economic attractiveness of lower transportation tariffs. Taking into account the additional financial and time costs of cargo transshipment, the first delivery option remains optimal.

Thus, the factors of intermodal transport development in national economies studied by Polish scholars [22–24] and the conclusions they have drawn are a fair reflection of the real state of affairs. The current compactness of the railroad network, especially in the east of Poland, does not always facilitate the use of this type of transport in international trade with Ukraine.

The limitations of the practical results of the calculations are associated with several factors:

Firstly, the scaling of input data, in our case, did not extend beyond the transportation networks in organizing optimal cargo delivery from Khmelnytskyi to Lublin. However, in general, the dimensionality of input data may increase.

Secondly, as recent events have demonstrated, force majeure circumstances and political decisions can significantly impact the duration of cargo transportation, making it unpredictable.

Thirdly, starting in February 2022, the State Statistics Service of Ukraine ceased the dissemination of a significant amount of statistical information in open access. The inability to obtain up-to-date data directly affects the accuracy of calculations.

Despite these challenges, this research has practical significance. The low development of intermodal freight transport between Poland and Ukraine is associated with the need for economic justification of such logistics chains, the results of which depend on solving optimization problems. That is, it is necessary to have an appropriate toolkit for this.

5. Conclusions

The volumes of international trade between countries, on the one hand, serve as an indicator of the openness of their economies and, on the other hand, directly influence the level of economic security and competitiveness of the domestic market. The statistical-economic analysis of the state of foreign trade between Poland and Ukraine showed that, due to a significant economic development lag, Ukraine was more dependent on these trade relations. According to 2021 data, Poland held the second position in Ukraine's external trade structure, with a share of 7.2%. Conversely, this indicator did not exceed 1.5% in the opposite direction.

At the same time, the structure of international trade is an indirect indicator of the economic development of countries. Currently, Ukraine mainly supplies raw materials to Poland, while in the opposite direction, more technologically advanced products of the processing industry are supplied. This trade structure is disadvantageous for Ukraine, so it should focus on innovative development. Practical recommendations in this case are aimed at the need to restructure the economy of the country that lags behind in technological development.

The current dynamics and market volumes allow a positive assessment of the growth potential of international trade between the two countries in the post-war period. Global logistics outsourcing practices have found reflection in the form of intermodal freight transport, the advantages of which include flexibility and global coverage, economic

efficiency and environmental friendliness, transportation security, and the potential for extensive use of modern information technologies. It was found that the share of intermodal transport in Poland in 2020 remained low and did not exceed 3.5%. In Ukraine, such statistical accounting was not conducted. The further effective development of foreign economic activity between countries should be based on the rapid adaptation of Ukrainian legislation in the field of international trade to EU legal norms. The direct development of intermodal transport should be ensured by a balanced regulatory policy for all participants and be based on economic feasibility.

The proposed economic-mathematical model based on graph theory allows optimizing logistic flows in international trade between Ukraine and Poland based on minimizing the cost of transportation services and time. The validation revealed that, due to the existing density of the railway network in eastern Poland, intermodal transport between the two countries is not always economically justified today. Therefore, their current development should be associated with specific supply chains. A promising direction for further research may be the detailed analysis of cost factors in the proposed model, which will increase its flexibility and calculation accuracy.

The scientific novelty of this work is the further development of the intermodal freight transport model based on multi-criteria optimization and the method of sequential steps, which, unlike existing models, takes into account the need to ensure the minimum cost and time of performing corresponding logistic services and can be applied to solving the problem of integrating logistics flows in Ukraine and Poland.

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