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Foreign trade of Ukraine in 2021-2022: a vector model for analysing the consequences of Russian aggression

Abstract. The article is devoted to the analysis of the impact of Russia's full-scale invasion on the structure and dynamics of Ukraine's foreign trade. The article proposes a vector model for analysing the initial data. The origin of coordinates in the space of trade flows of a certain country can be interpreted in two ways - depending on its geopolitical goal. For a country that seeks to increase its influence on the global economy, the origin of coordinates is a state of its zero global significance. From the point of view of a country that has chosen a course of isolation from the global economy, the origin of coordinates is a state of absolute autarky. The vector norm (length) of trade turnover (or export) will characterise the absolute value of the result of its efforts. The proposed model is based on geometric properties of vector sums and differences. The ratios of these values were used to construct two types of vector convergence coefficients. Convergence coefficients calculated by the sum method were determined as the ratio of the norm of vector sums to the sum of their norms. Convergence coefficients calculated by the difference method were determined as the ratio of the difference of vector norms to the norm of their difference. The more similar the structure of the compared vectors is, the closer to 100% the modulus of their convergence coefficients approaches. The analysis of Ukraine's foreign trade was carried out in several coordinate systems - on the plane of Exports - Imports, in the space of three groups of goods (capital goods, consumer goods, intermediate goods), in the space of countries and on the plane of Flows 2021 - Flows 2022. A comparative analysis of scalar and vector models has shown that the proposed model is the lower bound of the correlation between the shares of exports in Ukrainian foreign trade in 2021 and 2022. A comparison of relative indicators of the volume of domestic foreign trade calculated on the basis of two models has shown that the discrepancy between them is small and does not violate the order of countries in the ranked series. Convergence coefficients of trade with European partners have shown the importance of the group of intermediate goods. The coefficients of

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domestic trade with the vast majority of regions and countries were in the “red zone” - the volume of trade in 2022 decreased, and the two-year volume of imports exceeded the two-year volume of exports. At the same time, the export-import structure of Ukrainian trade changed little. The proposed vector model can serve as a tool in a wide range of international research, primarily of a geopolitical orientation

Keywords: international comparative studies, trade flow vector, DEA model, capital goods, consumer goods and intermediate goods, foreign trade indicators, geopolitical factors of foreign economic activity

Introduction

Economic consequences of Russia's long-term aggression determine both the course of current events of national resistance and political and economic future of Ukraine. Foreign trade has been a key component of national GDP for decades. Since 2014, significant changes have been taking place in sectoral and geographical structure of Ukraine's foreign trade. In addition to direct losses of economic and export potential as a result of Russian occupation of part of Ukrainian territory and physical destruction of assets, it is also influenced by national and international rehabilitation regimes introduced against the aggressor country.

With the beginning of the full-scale invasion in 2022, the European Union countries agreed on trade preferences for Ukrainian exports. A duty-free trade regime was introduced for 30 groups of Ukrainian goods; the application of the system of input prices for goods, where it was determined, import tariff quotas for goods and protective measures was suspended. In 2024, quotas for 40 items of Ukrainian agricultural exports, which became “sensitive” for the European market, were added to current trade regime. These measures made it possible to significantly support Ukrainian economy, preserve foreign exchange earnings in the country, and support the consolidated budget and government expenditures. On June 6, 2025, the EU decided to cancel the duty-free trade regime, and at the same time, to restore the terms of the Deep and Comprehensive Free Trade Area (DCFTA) with Ukraine.

Systemic support for Ukraine by the European Union has strengthened its position as a leading foreign economic partner. According to the Ministry of Economy, in 2024, the EU exported goods to Ukraine worth €42.8 billion and imported €24.5 billion. It resulted in trade surplus of €18.3 billion. During the period of trade preferences, Ukrainian exporters managed to reorient themselves from the key export direction - through the Black Sea - to automobile and railway transport logistics. The development of a common policy for resolving controversial issues in mutual trade was an important result of partnership interaction. According to the conclusions of representatives of the European Business Association (EBA), the years of visa-free exports enabled Ukrainian business to gain expanded access to foreign competitive markets as a new promising direction of development.

The future of Ukraine's foreign trade in global markets will depend on the competitiveness of exported goods and the effectiveness of foreign economic policy in terms of both state strategy and competitive business strategies. The experience of Ukraine's foreign trade during the period of the full-scale invasion makes it possible to determine the potential for further changes in its commodity and geographical structure, the criteria for the formation of sustainable foreign trade flows to support national financial and economic stability.

Literature review

With the beginning of the full-scale invasion, economic consequences of Russian aggression have become one of the leading topics of domestic and foreign research.

During this period, the articles by I. Baranenko and I. Privarnikova (2023) and D. V. Kulish (2023) have become one of the first domestic works. I. Baranenko and I. Privarnikova devoted their article to the study of trends in Ukraine's foreign trade in agricultural products. As the authors note, “Ukrainian exports are dominated by the category of products of vegetable origin, the share of

which is increasing every year, while the share of finished products, on the contrary, is decreasing". Having analysed logistical problems caused by the full-scale invasion, I. Baranenko and I. Privarnikova (2023, p. 15) concluded that maritime transport remained key in the exports of these products. D. V. Kulish also drew attention to logistical problems. The researcher notes that "more than half of crop production in Ukraine is exported", but the occupation and blocking of Azov and Black Sea ports led to a multiple drop in exports. Although Russian aggression has already affected our trading partners, other countries are not yet feeling it to the full extent (Kulish, p. 8).

The study by A. Sadłowski and A. Zając (2024) aimed "to identify barriers to the efficient flow of agricultural products from Ukraine along the European Union (EU) solidarity lanes that pass through the territory of Poland" and to develop recommendations for improving transit. The attention of Polish scientists was paid to the importance of social support for the success of the project (Sadłowski & Zając, 2024, p. 29).

Positive consequences of the resumption of Ukrainian grain exports were analysed by V. Halkin (2024). In his study, the author used methods such as SWOT-analysis, benchmarking and analysis of the change in the global Food Price Index and certain types of products (2009-2024). A. Simakhova (2024) used SWOT-analysis to study the war impact on Ukrainian foreign trade. The researcher analysed the change in the commodity pattern and structure of foreign trade by types of services in 2022.

The transformation of Ukraine's trade with the European Union was analysed in the article by O. Shnyrkov *et al.* (2025). The researchers note that "further liberalisation of trade relations between the EU and Ukraine amid the aggression contributed to maintaining and increasing exports to EU member states" (Shnyrkov *et al.*, 2025, p. 301).

The article by Romanian and Ukrainian scholars (Nate *et al*., 2024) systematically investigated the geoeconomic significance of the Black Sea region. The authors analysed 1,764 econometric models that reflected Turkey's mediating role, the changing role of the EU, the Middle East and Russia, as well as, very importantly, the potential resurgence of Ukraine. In their opinion, "the post-conflict landscape could witness heightened Western influence and continued Chinese engagement" (Nate *et al*., 2024, p. 256).

Ukraine's maritime trade from 2010 to December 2024 became the subject of research by a team of scientists from Spain, France and Italy (Martin *et al*., 2025). To analyse its dynamics, the authors proposed a threefold strategy based on network models. In their study, the authors took into account that Russia's armed confrontation with Ukraine started back in 2014. The final conclusion of their study is that "the resilience of Ukrainian logistics network is achieved through reallocation to other routes and transport modes" (Martin *et al*., 2025, p. 1).

A joint study by A. M. Countryman and Ukrainian scientists (Countryman *et al*., 2024) has found that Russian-Ukrainian war is already raising global prices for agricultural and food products and threatening their global affordability. This research employs a computable general equilibrium model to predict global consequences of the Black Sea blocking. The results show "net global welfare losses ranging from more than $5 billion to nearly $20 billion depending on the success of transport through European Solidarity Lanes" (Countryman *et al*., 2024, p. 1). However, as the team of lecturers of Khmelnytskyi National University (Dykha *et al*., 2024) rightly noted, for each of the challenges, ways to overcome them and methods to turn them into additional opportunities were developed. In particular, these include diversification of logistics routes, increasing the value of human capital, developing alternative energy sources and moving closer to sustainable development goals (Dykha *et al*., 2024, p. 31). A similar point of view is advocated by the team of law professors and officials of Ukrainian law enforcement agencies (Rohatiuk *et al*., 2024). The authors argue that "legal and institutional reforms, alongside strategic efforts to enhance market competition, investment climate, and technological innovation, are crucial for sustaining economic growth amidst conflict" (Rohatiuk *et al*., 2024, p. 78). Statistical confirmation of this opinion is presented in a collective article by scientists from Slovakia, Poland and Ukraine (Yehorova *et al*., 2024). The

authors analysed the dynamics of the Foreign Economic Security Index of Ukraine for the period 2023-2024. Their study showed that "the growth of foreign economic security is recorded in the period of stabilisation during the implementation of structural reforms: 2005-2008 - the period after the Orange Revolution, 2014-2016 - the period of growth after the Revolution of Dignity, 2021 - post-pandemic recovery" (Yehorova *et al*., 2024, p. 382).

An optimistic scenario for the recovery of Ukrainian economy is presented in a study by a team of researchers from several Ukrainian universities (Petrukha *et al*., 2025). The findings indicate "moderate economic growth, declining inflation, and a reduced key policy rate in 2025", with stronger recovery anticipated in 2026-2027. According to their expectations, "budget deficits are expected to be financed by external loans and grants, primarily directed to the defence sector". The authors of the study predict that "economic recovery drivers will centre on directing international assistance toward structural weaknesses in Ukraine's economy, promoting innovation, and enabling the return of highly skilled migrants" (Petrukha *et al*., 2025, p. 196).

It should be noted that the shadow aspect of Ukrainian trade has not been ignored by Ukrainian scholars. Thus, the article by O. Y. Shostko *et al.* (2025) describes and explains the patterns of changes in domestic illicit trade and related transnational illicit flows of goods, services and money during the extreme social crises based on the case of the war in Ukraine (Shostko *et al*., 2025, p. 1).

Fundamentally important issues of EU security policy are raised in an article by D. Genini (2025), an employee of several Irish educational and scientific institutions. As the author notes, Russia's full-scale invasion of Ukraine on 24 February 2022 dismantled the "illusion of perpetual peace". In response to this aggression, the EU has provided substantial support to Ukraine and expanded its defence industry. However, the scientist draws attention to the fact that "critical questions remain: Have these efforts been sufficient to secure the EU's geopolitical relevance in Europe?" The author's research argues that the CFSP is at a defining crossroads: the EU must either implement significant reforms to strengthen its geopolitical influence in an increasingly volatile world or risk being relegated to the status of a purely economic actor with a diminished global standing" (Genini, 2025, p. 1).

A research report prepared by employees of the Bank of Finland Institute for Emerging Economies (Korhonen *et al*., 2025) examined Russia's economic prospects. The authors of the report conclude that some changes such as the degraded business environment and increased government presence in the economy are likely to persist and the war has also exacerbated Russia's already poor demographic trends. A break in the war and relaxation of sanctions would eventually at least partially reinvigorate Russian trade with the European Union, but would not reduce its dependence on China. In all scenarios considered by the authors of the report, "Russia's share of the global economy continues to decline. Russia, however, has the resources it needs to continue the war, the desire to fund its armed forces and the commitment to support its military-industrial complex come what may" (Korhonen *et al*., 2025, p. 3).

Emphasis is placed differently in the article by the Chinese scholar Y. Liu (2025). In his opinion, Russian-Ukrainian war began only in 2022 and is gradually turning into a war between Russia and Europe. The author applies four models of international relations, in particular the model of "Third Party Consideration", but concludes that the Relative Gains framework most effectively explains the behaviour of Russia and the EU (Liu, 2025, p. 13).

Materials and methods

The volumes of exports and imports of a country are the basic indicators characterising its foreign trade. For certain types of products, statistical data can reflect both physical and value volumes of trade flows. However, the volumes of trade in aggregated groups of products are usually measured in terms of value. The value method of measurement makes it possible to compare the volumes of trade in any goods, to compare them with financial flows and the value of gross domestic product. Given the huge amount of statistical data, the authors of the proposed study limited themselves to

three groups of goods - capital goods, consumer goods and intermediate goods. Comprehensive information on these groups of products is presented on the WITS (World Integrated Trade Solution) website - a system created by the World Bank. WITS provides data on bilateral trade between countries based on different classifications of products, years and trade flows. At the time of the beginning of this study, the latest data on domestic trade by aggregated groups of goods characterised 2021 and 2022. However, these years are fundamental for characterising the radical change in the state of Ukraine's foreign trade and the economy as a whole.

The authors of the proposed article focused on a comparative analysis of trade flows (exports and imports) between Ukraine and other countries. In accordance with the World Bank approach, all the countries studied were grouped into the following regions - Europe & Central Asia, Middle East & North Africa, East Asia & Pacific, North America, South Asia and the World. The Latin America & Caribbean and Sub-Saharan Africa regions were not considered due to their significantly lower weight in Ukrainian foreign trade. The Europe & Central Asia region was further divided into three subregions: 1) aggressor countries (Russia and its satellite Belarus), 2) the European Union and European countries integrated with it (in particular Albania, Bosnia and Herzegovina, Iceland, Moldova, Montenegro, North Macedonia, Norway, Serbia, Switzerland, United Kingdom), 3) Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan), the South Caucasus (Armenia, Azerbaijan, Georgia) and Turkey. Given the geopolitical importance for Ukraine, some indicators were also calculated for Iran and Israel.

Usually, comparative international studies use normalised indicators. Different methods of their construction are possible. However, in many cases, comparisons of absolute values of the same name are also important. In particular, such comparisons are traditional in the analysis of exports and imports. This approach was used as the basis of the proposed study. In the future, it can serve as a foundation for research using normalised indicators.

From a mathematical point of view, all theoretical models of the economy can be divided into scalar and vector-matrix ones. The second class of models is widely represented primarily in studies of inter-branch flows of products and services. In foreign trade studies, they are much less common. Equations of such models usually contain scalar products of product flow vectors and matrices of certain coefficients. Historically, the Leontief model is the first and classic example of this class of models. However, the vector norm (length), which is its important mathematical characteristic, has not yet become a generally recognised tool of economic science. The study of metric and normed spaces is the subject of a separate branch of mathematics - functional analysis. The proposed work makes an attempt to apply vector norms to the analysis of Ukraine's foreign trade in three coordinate systems: on the plane of Exports - Imports, in the space of three groups of goods and on the plane of Flows 2021 - Flows 2022. According to the authors, the calculation and comparison of vector norms can significantly expand the set of indicators used in theoretical and analytical research.

The turnover of foreign trade is one of its popular indicators. It is the sum of the value of exports and imports of a certain C_ς country for a certain t_τ period:

$$\mathcal{FT}_{\varsigma\tau} = \mathcal{EX}_{\varsigma\tau} + \mathcal{IM}_{\varsigma\tau}. \quad (1)$$

On the plane of Exports - Imports, its state will be displayed as a $(\mathcal{EX}_{\varsigma\tau}, \mathcal{IM}_{\varsigma\tau})$ point (Figure 1). This point can be considered as the sum of $(\mathcal{EX}_{\varsigma\tau}, 0)$ and $(0, \mathcal{IM}_{\varsigma\tau})$ vectors:

$$\overrightarrow{\mathcal{FT}}_{\varsigma\tau} = \overrightarrow{\mathcal{EX}}_{\varsigma\tau} + \overrightarrow{\mathcal{IM}}_{\varsigma\tau}. \quad (2)$$

The sum of the norms of export and import vectors is foreign trade turnover:

$$\left\|\overrightarrow{\mathcal{EX}}_{\varsigma\tau}\right\| + \left\|\overrightarrow{\mathcal{IM}}_{\varsigma\tau}\right\| = \sqrt{\mathcal{EX}_{\varsigma\tau}^2 + 0^2} + \sqrt{0^2 + \mathcal{IM}_{\varsigma\tau}^2} = \mathcal{FT}_{\varsigma\tau}. \quad (3)$$

The norm of trade flow vectors is less than the value of trade turnover and is equal to the square root of the sum of the squares of exports and imports:

$$\left\|\overrightarrow{\mathcal{EX}}_{\varsigma\tau}\right\| + \left\|\overrightarrow{\mathcal{IM}}_{\varsigma\tau}\right\| > \left\|\overrightarrow{\mathcal{FT}}_{\varsigma\tau}\right\| = \sqrt{\mathcal{EX}_{\varsigma\tau}^2 + \mathcal{IM}_{\varsigma\tau}^2}. \quad (4)$$

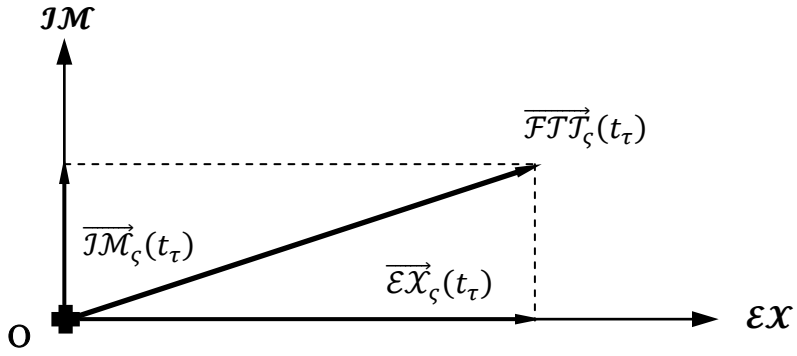

Figure 1. Vector model of the country's foreign trade on the plane of Exports - Imports
Source: I. Zagoruyiko's model

This value can be interpreted in two ways. From the point of view of a country choosing a course of isolation from the global economy, $\left\|\overrightarrow{\mathcal{FTT}_{\varsigma\tau}}\right\|$ will serve as an indicator of absolute value of dependence on foreign trade. For it, the origin of coordinates is the state of absolute autarky. From the point of view of a country seeking to increase its influence on the global economy, $\left\|\overrightarrow{\mathcal{FTT}_{\varsigma\tau}}\right\|$ will characterise absolute value of the result of its efforts. For it, the origin of coordinates is the state of its zero global significance.

Economic properties of the norm of trade flow vectors can be illustrated by two opposite examples.

If the country refuses to import and increases the amount of its exports by the amount

Let the state of a country in a certain period be characterised by non-zero values of its exports and imports: $\mathcal{EX}_{\varsigma}(t_0) > 0$, $\mathcal{IM}_{\varsigma}(t_0) > 0$. If the country refuses to import and increases its exports by $\mathcal{IM}_{\varsigma}(t_0)$ value, then its foreign trade turnover will not change: $\mathcal{FTT}_{\varsigma}(t_1) = \mathcal{EX}_{\varsigma}(t_1) = \mathcal{EX}_{\varsigma}(t_0) + \mathcal{IM}_{\varsigma}(t_0)$. However, from a qualitative point of view, foreign economic position of this country will change radically. Its distance to the state of absolute autarky will increase: $\mathcal{EX}_{\varsigma}^2(t_1) > \mathcal{EX}_{\varsigma}^2(t_0) + \mathcal{IM}_{\varsigma}^2(t_0)$.

The opposite situation will arise if, in the next period, the country reduces its exports and starts importing again in such a way that its distance to the state of zero global significance does not change: $\mathcal{EX}_{\varsigma}(t_2) < \mathcal{EX}_{\varsigma}(t_1)$, $\mathcal{IM}_{\varsigma}(t_2) > \mathcal{IM}_{\varsigma}(t_1) = 0$, $\mathcal{EX}_{\varsigma}^2(t_2) + \mathcal{IM}_{\varsigma}^2(t_2) = \mathcal{EX}_{\varsigma}^2(t_1)$. In this case, its foreign trade turnover will increase: $\mathcal{EX}_{\varsigma}(t_2) + \mathcal{IM}_{\varsigma}(t_2) > \mathcal{EX}_{\varsigma}(t_1)$.

A geometric interpretation of these cases is presented in Figure 2.

In vector models, it is possible to introduce values that will be analogues of the shares of exports and imports in trade turnover. These vector analogues will be equal to the ratio of the square of a certain trade flow of a p_ϱ product to the sum of the squares of its exports and imports:

$$\frac{\mathcal{EX}_{\varsigma\varrho\tau}}{\mathcal{EX}_{\varsigma\varrho\tau} + \mathcal{IM}_{\varsigma\varrho\tau}} \Rightarrow \cos^2\varphi = \frac{\mathcal{EX}_{\varsigma\varrho\tau}^2}{\mathcal{EX}_{\varsigma\varrho\tau}^2 + \mathcal{IM}_{\varsigma\varrho\tau}^2}, \tag{5}$$

$$\frac{\mathcal{IM}_{\varsigma\varrho\tau}}{\mathcal{EX}_{\varsigma\varrho\tau} + \mathcal{IM}_{\varsigma\varrho\tau}} \Rightarrow \sin^2\varphi = \frac{\mathcal{IM}_{\varsigma\varrho\tau}^2}{\mathcal{EX}_{\varsigma\varrho\tau}^2 + \mathcal{IM}_{\varsigma\varrho\tau}^2}, \tag{6}$$

where φ - the angle of inclination of $\overrightarrow{\mathcal{FTT}_{\varsigma\varrho\tau}}$ vector to the abscissa axis.

In the space of products, the vector analogue of the share of exports will take the form:

$$\frac{\mathcal{EX}_{\varsigma\varrho\tau}}{\mathcal{EX}_{\varsigma\varrho\tau} + \mathcal{IM}_{\varsigma\varrho\tau}} \Rightarrow \frac{\left\|\overrightarrow{\mathcal{EX}_{\varsigma\tau}}\right\|}{\left\|\overrightarrow{\mathcal{EX}_{\varsigma\tau}}\right\| + \left\|\overrightarrow{\mathcal{IM}_{\varsigma\tau}}\right\|}. \tag{7}$$

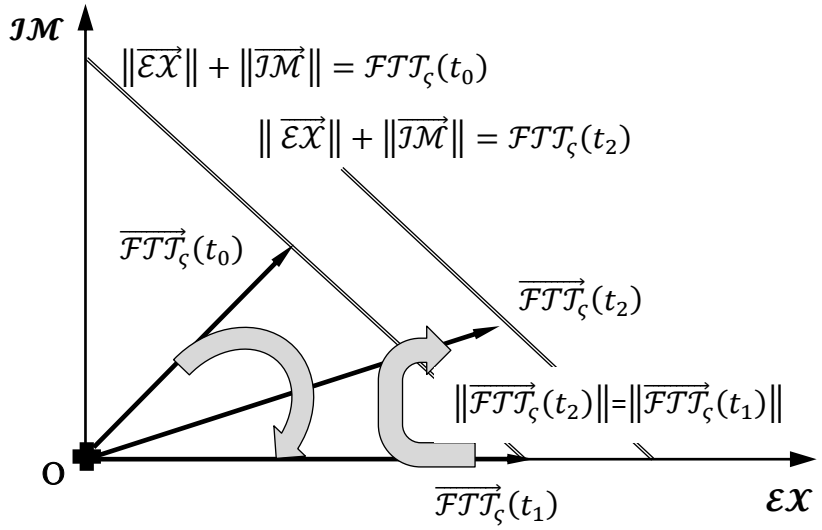

Figure 2. Consequences of the change in the country's foreign trade policy on the plane of Exports - Imports

Source: I. Zagoruyiko's model

In addition to the share of exports in trade turnover, the share of a certain p_{ϱ} product turnover in the total turnover of all products in one year and the share of p_{ϱ} product turnover in t_{τ} year in its total turnover over several years can be calculated:

$$\frac{\mathcal{FTT}_{\varsigma\tau}(p_{\varrho})}{\sum_i \mathcal{FTT}_{\varsigma\tau}(p_i)} \Rightarrow \frac{\|\overrightarrow{\mathcal{FTT}_{\varsigma\tau}}(p_{\varrho})\|}{\sum_i \|\overrightarrow{\mathcal{FTT}_{\varsigma\tau}}(p_i)\|}, \tag{8}$$

$$\frac{\mathcal{FTT}_{\varsigma\varrho}(t_{\tau})}{\sum_j \mathcal{FTT}_{\varsigma\varrho}(t_j)} \Rightarrow \frac{\|\overrightarrow{\mathcal{FTT}_{\varsigma\varrho}}(t_{\tau})\|}{\sum_j \|\overrightarrow{\mathcal{FTT}_{\varsigma\varrho}}(t_j)\|}. \tag{9}$$

A comparison of these indicators of the scalar model with similar indicators of the vector model was used to assess the discrepancy between the two models.

The proposed model makes it possible to analyse the structure of foreign trade of the studied country from different points of view. Ukraine is such a country in this article. On the plane of Exports - Imports, these can be the following areas of analysis of domestic foreign trade:

- comparison of the structure of trade in different products with one country for a certain year;
- comparison of the structure of trade in one product with different countries for a certain year;
- comparison of the structure of trade in one product with one country for two different years.

Given the number of product groups and trade partners of Ukraine, the analysis of the first two structures was carried out based on the triangle inequality. It consists in the fact that the sum of its two sides is not less than the third side. In functional analysis, this property is formulated as follows: the norm of the sum of two vectors does not exceed the sum of their norms. It follows that the ratio of the norm of the sum of several vectors to the sum of their norms is not more than one. From economic point of view, this ratio can be interpreted as the coefficient of convergence of the export-import structure of studied vectors - the smaller the differences in their structure are, the less their angles of inclination will differ and the less they will deviate from the sum vector. A situation of a small deviation from the sum vector may also arise in the case when the norm of one of the vectors significantly exceeds the norms of the rest.

In the case of studying the structure of domestic trade in different products with C_{ς} country for t_{τ} year, the convergence coefficient was calculated as

$$\mathbb{conv}\sum_i \overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_i, t_\tau\right) = \frac{\left\|\sum_i \overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_i, t_\tau\right)\right\|}{\sum_i \left\|\overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_i, t_\tau\right)\right\|} \le 1 \qquad i = 1, 2, \dots \varrho, \dots \mathrm{P}, \tag{10}$$

where i - product number.

In the case of studying the structure of domestic trade in p_ϱ product with different countries for t_τ year, the convergence coefficient was calculated as

$$\mathbb{conv}\sum_h \overrightarrow{\mathcal{FTT}}\left(C_h, p_\varrho, t_\tau\right) = \frac{\left\|\sum_h \overrightarrow{\mathcal{FTT}}\left(C_h, p_\varrho, t_\tau\right)\right\|}{\sum_h \left\|\overrightarrow{\mathcal{FTT}}\left(C_h, p_\varrho, t_\tau\right)\right\|} \le 1 \qquad h = 1, 2, \dots \varsigma, \dots \mathrm{K}, \tag{11}$$

where h - country number.

A geometric interpretation of two types of sums of studied vectors is presented in Figure 3.

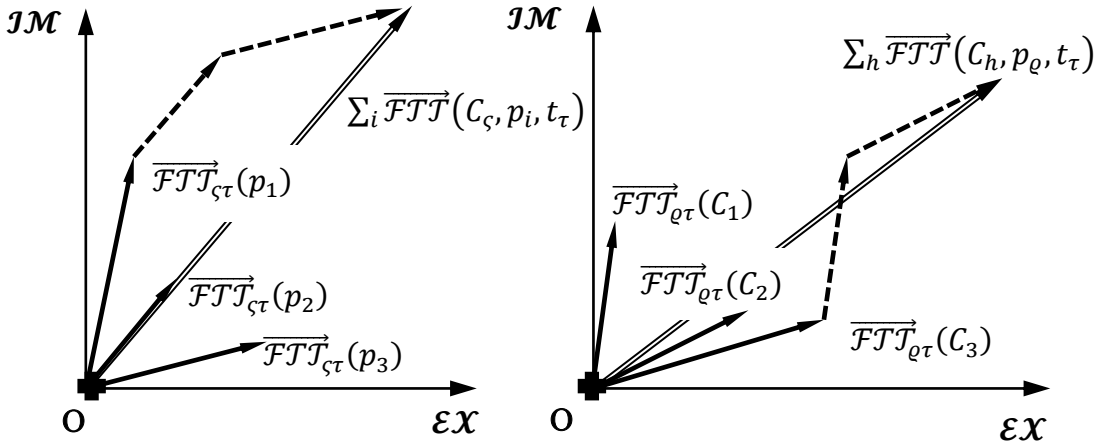

Figure 3. Sums of trade flow vectors of different products and different countries on the plane of Exports - Imports

Source: I. Zagoruyiko's model

The study of the structure of domestic trade in one product with one country for two different years can also be carried out using the vector sum method. However, an alternative method - the vector difference method - can also be used. It is based on the geometric fact that the difference of two sides of a triangle is not greater than its third side. From the point of view of functional analysis, this property will be expressed as the fact that the modulus of the difference of the norms of two vectors is not greater than the norm of their difference. The convergence coefficient calculated using the vector difference method will have the form:

$$\mathbb{conv}\Delta_t \overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_\varrho, t\right) = \frac{\left\|\overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_\varrho, t_{2022}\right)\right\| - \left\|\overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_\varrho, t_{2021}\right)\right\|}{\left\|\overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_\varrho, t_{2022}\right) - \overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_\varrho, t_{2021}\right)\right\|}, \tag{12}$$

$$-1 \le \mathbb{conv}\Delta_t \overrightarrow{\mathcal{FTT}}\left(C_\varsigma, p_\varrho, t\right) \le +1.$$

A geometric interpretation of the method of the difference of two studied vectors is presented in Figure 4.

It should be noted, however, that the vector difference method also has certain limitations. First, it cannot be applied if the compared vectors coincide. Second, if the norms of two vectors are equal, then this convergence coefficient will be equal to zero regardless of the difference in the angles of inclination of vectors. Thus, the closer to zero the value of this coefficient is, the less it reflects the similarity of vector structures and the more - the closeness of their norms.

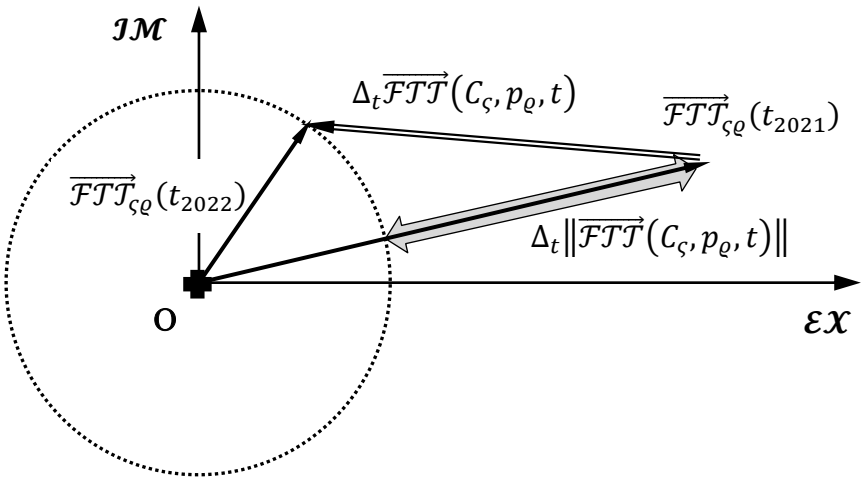

Figure 4. The method of the difference of trade flow vectors of two years on the plane of Exports - Imports

Source: I. Zagoruyiko's model

The study of the remaining types of domestic trade structures was carried out in other spaces. Thus, in the space of products, the following convergence coefficients were constructed:

- coefficient of convergence of export and import flows carried out between Ukraine and a certain foreign trade partner in a certain year

$$\mathbb{conv}\left(\overrightarrow{\mathcal{EX}} - \overrightarrow{\mathcal{IM}}\right)_{\varsigma\tau} = \frac{\left\|\overrightarrow{\mathcal{EX}}(C_\varsigma, t_\tau)\right\| - \left\|\overrightarrow{\mathcal{IM}}(C_\varsigma, t_\tau)\right\|}{\left\|\overrightarrow{\mathcal{EX}}(C_\varsigma, t_\tau) - \overrightarrow{\mathcal{IM}}(C_\varsigma, t_\tau)\right\|}, \tag{13}$$

- coefficient of convergence of export (or import) flows carried out between Ukraine and a certain foreign trade partner in two different years

$$\mathbb{conv}\Delta_t\overrightarrow{\mathcal{EX}}(C_\varsigma, t) = \frac{\left\|\overrightarrow{\mathcal{EX}}(C_\varsigma, t_{2022})\right\| - \left\|\overrightarrow{\mathcal{EX}}(C_\varsigma, t_{2021})\right\|}{\left\|\overrightarrow{\mathcal{EX}}(C_\varsigma, t_{2022}) - \overrightarrow{\mathcal{EX}}(C_\varsigma, t_{2021})\right\|}, \tag{14}$$

$$\mathbb{conv}\Delta_t\overrightarrow{\mathcal{IM}}(C_{\varsigma,}, t) = \frac{\left\|\overrightarrow{\mathcal{IM}}(C_\varsigma, t_{2022})\right\| - \left\|\overrightarrow{\mathcal{IM}}(C_\varsigma, t_{2021})\right\|}{\left\|\overrightarrow{\mathcal{IM}}(C_\varsigma, t_{2022}) - \overrightarrow{\mathcal{IM}}(C_\varsigma, t_{2021})\right\|}. \tag{15}$$

In the space of countries, the coefficients of convergence of export and import vectors of a certain product were constructed using two methods - the sum method and the difference method:

$$\mathbb{conv}\left(\overrightarrow{\mathcal{EX}} + \overrightarrow{\mathcal{IM}}\right)_{\varrho\tau} = \frac{\left\|\overrightarrow{\mathcal{EX}}(p_\varrho, t_\tau) + \overrightarrow{\mathcal{IM}}(p_\varrho, t_\tau)\right\|}{\left\|\overrightarrow{\mathcal{EX}}(p_\varrho, t_\tau)\right\| + \left\|\overrightarrow{\mathcal{IM}}(p_\varrho, t_\tau)\right\|}, \tag{16}$$

$$\mathbb{conv}\left(\overrightarrow{\mathcal{EX}} - \overrightarrow{\mathcal{IM}}\right)_{\varrho\tau} = \frac{\left\|\overrightarrow{\mathcal{EX}}(p_\varrho, t_\tau)\right\| - \left\|\overrightarrow{\mathcal{IM}}(p_\varrho, t_\tau)\right\|}{\left\|\overrightarrow{\mathcal{EX}}(p_\varrho, t_\tau) - \overrightarrow{\mathcal{IM}}(p_\varrho, t_\tau)\right\|}. \tag{17}$$

In the space of Trade flows 2021 - Trade flows 2022, the corresponding convergence coefficient was constructed using the difference method

$$\mathbb{conv}\left(\overrightarrow{\mathcal{EX}} - \overrightarrow{\mathcal{IM}}\right)_{\varsigma\varrho} = \frac{\left\|\overrightarrow{\mathcal{EX}}(C_\varsigma, p_\varrho)\right\| - \left\|\overrightarrow{\mathcal{IM}}(C_\varsigma, p_\varrho)\right\|}{\left\|\overrightarrow{\mathcal{EX}}(C_\varsigma, p_\varrho) - \overrightarrow{\mathcal{IM}}(C_\varsigma, p_\varrho)\right\|}. \tag{18}$$

Results and discussion

The ability of the vector model of foreign trade to confirm correlation dependencies identified on the basis of the scalar model is an important criterion for the feasibility of its using. To test this property, the "Share of exports in foreign trade of Ukraine" indicator was chosen. It was previously assumed that the greater the weight of domestic exports in trade with a certain country in 2021 was, the greater it should have been after Russia's full-scale invasion. This assumption was tested on a group of countries classified by the World Bank as Europe & Central Asia region. For geopolitical reasons, Russia and its satellite Belarus were excluded from this sample.

In the scalar model, the specific weight of exports in foreign trade turnover in 2021 was chosen as an independent variable and its specific weight in 2022 as a dependent one. The existence of a correlation was verified using two regression equations - linear and quadratic ones:

$$\hat{x}(p_i, t_{2022}) = a_0 + a_1 x(p_i, t_{2021}), \tag{19}$$

$$\hat{x}(p_i, t_{2022}) = b_0 + b_1 x(p_i, t_{2021}) + b_2 x^2(p_i, t_{2021}), \tag{20}$$

$$x_t(C_\varsigma, p_i) = \frac{\mathcal{EX}_t(C_\varsigma, p_i)}{\mathcal{EX}_t(C_\varsigma, p_i) + \mathcal{IM}_t(C_\varsigma, p_i)}, \quad i = 1, 2, 3, 4\,, \tag{21}$$

$$\hat{y}(t_{2022}) = a_0 + a_1 y(t_{2021}), \tag{22}$$

$$\hat{y}(t_{2022}) = b_0 + b_1 y(t_{2021}) + b_2 y^2(t_{2021}), \tag{23}$$

$$y_t(C_\varsigma) = \frac{\sum_{i=1}^{3} \mathcal{EX}_t(C_\varsigma, p_i)}{\sum_{i=1}^{3} \mathcal{EX}_t(C_\varsigma, p_i) + \sum_{i=1}^{3} \mathcal{IM}_t(C_\varsigma, p_i)}, \tag{24}$$

where $\mathcal{EX}_t(C_\varsigma, p_i)$, $\mathcal{IM}_t(C_\varsigma, p_i)$ - volumes of Ukrainian exports and imports of the i-th product in trade with C_ς country. On the plane of Exports - Imports, capital goods were considered to be the first product, consumer goods - the second one, and intermediate goods - the third one. Final goods, the exports and imports of which were calculated as the sums of the corresponding values of capital and consumer goods, were considered to be the fourth product. In the space of three products, total values of exports and imports were calculated as the sums of the corresponding values of capital, consumer and intermediate goods.

In the vector model on the plane of Exports - Imports, the squares of exports divided by the sum of the squares of exports and imports were used as variables:

$$v_t(C_\varsigma, p_i) = \frac{\mathcal{EX}_t^2(C_\varsigma, p_i)}{\mathcal{EX}_t^2(C_\varsigma, p_i) + \mathcal{IM}_t^2(C_\varsigma, p_i)}, \qquad i = 1, 2, 3, 4, \tag{25}$$

$$\hat{v}(p_i, t_{2022}) = a_0 + a_1 v(p_i, t_{2021}), \tag{26}$$

$$\hat{v}(p_i, t_{2022}) = b_0 + b_1 v(p_i, t_{2021}) + b_2 v^2(p_i, t_{2021}). \tag{27}$$

In the space of three products, the ratio of the norm of export vector to the sum of export and import norms were the variables of the vector model:

$$w_t(C_\varsigma) = \frac{\left\| \overrightarrow{\mathcal{EX}_t}(C_\varsigma) \right\|}{\left\| \overrightarrow{\mathcal{EX}_t}(C_\varsigma) \right\| + \left\| \overrightarrow{\mathcal{IM}_t}(C_\varsigma) \right\|}, \tag{28}$$

$$\hat{w}(t_{2022}) = a_0 + a_1 w(t_{2021}), \tag{29}$$

$$\hat{w}(t_{2022}) = b_0 + b_1 w(t_{2021}) + b_2 w^2(t_{2021}). \tag{30}$$

Table 1 shows the parameters of regression equations of both models on the plane of Exports - Imports and in the space of three products. As the table data show, all regression equations show a positive dependence of export shares before and after the full-scale invasion. At the same time, quadratic equations described this dependence better than linear ones, as follows from the

comparison of their coefficients of determination ($R^2_{quadr} > R^2_{lin}$). For both models, R^2 coefficient of determination was quite high, especially for consumer and final goods on the plane of Exports - Imports and in the space of three products. All regression equations of the vector model showed a weaker correlation of variables than the corresponding equations of the scalar model ($R^2_{vect} < R^2_{sc}$). On this basis, it can be assumed that in the cases of other variables, the vector model will act as the lower bound of the correlation-regression relationship, and the scalar model - as the upper bound.

Table 1. Parameters of regression equations of export shares in Ukraine's foreign trade with the countries of Europe and Central Asia in 2021-2022

Parameters of equations and R^2	Plane of Exports - Imports								Space of capital goods - Consumer goods - Intermediate goods	
	Capital goods p_1		Consumer goods p_2		Intermediate goods p_3		Final goods p_4			
	Scalar model	Vector model	Scalar model	Vector model	Scalar model	Vector model	Scalar model	Vector model	Scalar model	Vector model
Linear regression equation										
a_0	0.1084	0.0946	0.0188	0.0156	0.0482	0.0825	0.0232	0.0141	0.0064	0.0099
a_1	0.7787	0.7689	0.8985	0.8758	0.8842	0.8305	0.8925	0.8809	0.8917	0.8616
R^2	0.6199	0.5844	0.8607	0.8206	0.7328	0.7065	0.8539	0.8020	0.8340	0.8073
ΔR^2	0.0355		0.0401		0.0263		0.0519		0.0267	
Square regression equation										
b_0	0.0668	0.0909	0.0644	0.0535	0.0708	0.0319	0.0775	0.0539	0.0836	0.0988
b_1	1.0957	0.8316	0.6171	0.4367	0.7806	1.1574	0.5517	0.4217	0.5196	0.4258
b_2	–0.3090	–0.0631	0.2825	0.4536	0.0925	–0.3010	0.3436	0.4766	0.3522	0.4156
R^2	0.6249	0.5845	0.8662	0.8302	0.7333	0.7121	0.8624	0.8151	0.8433	0.8202
ΔR^2	0.0404		0.0360		0.0212		0.0473		0.0231	

Notes: 1) in the scalar model, the variables were calculated as exports to a certain country divided by the sum of exports and imports; 2) on the plane of Exports - Imports, the variables of the vector model were calculated as the square of exports to a certain country divided by the sum of the squares of exports and imports; 3) in the space of products, each coordinate axis displays all trade flows of a certain product; 4) in the space of products, the variables of the vector model were calculated as the length of the vector of exports to a certain country divided by the sum of the lengths of export and import vectors; 5) the share of exports in 2021 was selected as the independent variable, and the share of exports in 2022 - as the dependent one; 6) Liechtenstein was excluded from all samples due to lack of data; 7) Andorra, San Marino and aggressor countries were excluded from all samples; 8) Tajikistan was additionally excluded due to lack of data from the sample on intermediate goods

Source: prepared by the authors based on data from the WITS website

For the equations of intermediate goods, the coefficients of determination of two models were the closest ones. This caused a smaller discrepancy in the coefficients of determination of the two models in the space of three products compared to their discrepancy on the plane of Exports - Imports for final goods. As expected, the coefficients of determination of the equations of final goods in both models turned out to be intermediate between the coefficients of capital and consumer goods. At the same time, the difference in the coefficients of determination of the two models increased.

The next stage of comparing the scalar and vector models was to calculate relative indicators of the volume of foreign trade of Ukraine with certain countries (see Appendices 1, 2, 3). The sum of exports and imports was used as the volume of foreign trade in the scalar model, and the norm of flow vector on the plane of Exports - Imports - in the vector model. For three groups of goods (capital, consumer and intermediate ones), the shares of the volume of one year in the total volume of two years were calculated. This share reflected the dynamics of the volume of Ukraine's foreign trade. To characterise the product structure of domestic foreign trade, the shares of a certain group of goods in the total trade in three products were calculated.

Given the large volume of data, partner countries were grouped according to the World Bank classification. For geopolitical reasons, the subgroups of Aggressor countries and EU+, which

included the member states of the European Union and countries integrated with it, were selected in the Europe & Central Asia group. Additionally, trade with European and Central Asian countries, with which Ukraine had the largest turnover in 2021, was analysed.

A comparison of calculated indicators showed that the discrepancy between the scalar and vector models does not exceed 5%, and in many cases is several hundredths of a percent. In some cases, the indicator was higher according to the scalar model, and in other cases - according to the vector model, which, however, did not violate the order of countries in the ranked series. This can be considered an argument for the feasibility of using both models together.

As the research showed, in 2022 there was a radical reduction in domestic trade with aggressor countries. Trade in capital goods decreased the most, in intermediate goods - somewhat less, and in consumer goods - even less.

The dynamics of trade with the rest of countries and regions was not so unambiguous.

Thus, trade in capital goods decreased with all trading partners, but to different degrees (see Appendix 1). Among the main Ukrainian partners, the decrease in trade with Hungary, the Netherlands, Poland, Romania and Turkey was very small, and with Sweden - the largest. Thus, immediately after the full-scale invasion, Ukraine managed to maintain ties with its closest neighbours in this market segment. The dynamics of trade with the EU+ group was practically identical to the decrease in trade with the world as a whole.

The dynamics of trade in intermediate goods was more controversial (see Appendix 3). Ukraine was able to increase trade in these goods with Bulgaria, Hungary, Poland, and especially with Romania. The volume of trade with the rest of the main European partners decreased. Trade with Italy and the United Kingdom was particularly affected. However, trade with the EU+ group decreased somewhat less than trade with the World.

The picture of the dynamics of trade in consumer goods was the best (see Appendix 2). The volume of trade in these goods with the countries of the Middle East and North Africa remained almost unchanged. Trade with the EU+ countries increased slightly, and with South Asia it almost doubled. Among the main European partners, the greatest progress was made in trade with Lithuania, the Netherlands, Romania and Turkey. The reduction in trade with the World was insignificant.

Russia's full-scale invasion led to certain changes in the product structure of Ukrainian foreign trade.

The share of capital goods in trade with the aggressors, which in 2021 was much smaller than the share of the whole world, fell even more. Instead, the specific weight of capital goods in trade with the World, Asia, North America, the Middle East and North Africa remained almost unchanged. The share of capital goods in trade with Slovakia almost halved. According to this indicator, the restructuring of trade with Sweden was the worst. Before the full-scale attack, capital goods accounted for more than half of the volume of mutual trade between the two countries. In 2022, this share fell to a third (see Appendix 1).

The main structural changes occurred in the groups of consumer and intermediate goods (see Appendices 2 and 3). The share of consumer goods in trade with the World and aggressor countries increased significantly, while the share of intermediate goods decreased significantly. Trade with the countries of South Asia, the Middle East, and North Africa underwent even greater changes in this direction. Before the invasion in 2021, the share of consumer goods in domestic trade with South Asia was at the level of ≈20%, and after the 2022 invasion, it significantly exceeded 50%. As for individual Ukrainian partners, it is worth noting the one and a half times increase in the share of consumer goods in trade with Italy, the Netherlands, and Turkey. In Ukrainian trade with Lithuania and Kazakhstan, the share of consumer goods reached more than 50% in 2021, and in 2022 it became even higher. In trade with the United Kingdom, this share was less than 50%, but became significantly higher. This trend also manifested itself in trade with Switzerland. Before the full-scale attack, consumer goods already accounted for more than three quarters of the volume of the total trade, and after it their share exceeded 80%.

The second part of the study of Ukrainian foreign trade consisted of the calculation and interpretation of vector convergence coefficients on the plane of Exports - Imports, in the spaces of trade flows of countries, product flows and flows of 2021, 2022.

Table 2 shows three types of convergence coefficients that characterise the similarity of the structure of Ukraine's trade with its European partners (excluding Turkey and the countries of the South Caucasus).

On the plane of Exports - Imports, the method of the sum of vectors of foreign trade turnover with studied countries was the only possible one. As has already been found out, the volume and specific weight of trade in consumer goods with the EU+ group increased. The corresponding indicators of trade in intermediate goods decreased, but much less than in trade in capital goods. These changes were reflected in some equalisation of the export-import structure of trade in consumer goods, and especially in intermediate goods. On the contrary, the export-import structure of trade in capital goods became more geographically heterogeneous. However, cumulative impact of changes in trade in consumer goods turned out to be greater, so the coefficient of convergence of turnover vectors for capital goods slightly increased.

In the space of countries' trade flows, convergence coefficients characterise the similarity of geographical structures of domestic exports and imports in trade with European partners. These coefficients were calculated by two alternative methods - the vector sum method and the vector difference method. According to both methods, the change in convergence coefficients occurred in the same directions as on the plane of Exports - Imports. Namely, convergence coefficients in the groups of consumer, intermediate and final goods increased by modulus, in the group of capital goods both coefficients decreased by modulus. At the same time, the dynamics of convergence coefficients by the difference method was much more noticeable than the dynamics of coefficients calculated by the sum method[1]. As Table 2 shows, intermediate goods were the only group of goods whose exports exceeded imports. In 2022, this positive difference increased significantly. Thus, it was trade in intermediate goods that became an important internal factor in financial stability of the national economy of Ukraine.

Table 2. Indicators of the export-import structure of Ukraine's foreign trade with European partners in 2021-2022

Vector	Capital goods		Consumer goods		Intermediate goods		Final goods	
	2021	2022	2021	2022	2021	2022	2021	2022
Coefficients of convergence of countries' vectors on the plane of Exports - Imports								
$\Sigma\overrightarrow{\mathcal{FTT}}$	96.77%	95.45%	96.01%	96.87%	93.55%	95.08%	96.50%	96.92%
Coefficients of convergence of export and import vectors in the space of countries								
$\overrightarrow{\mathcal{EX}} + \overrightarrow{\mathcal{IM}}$	96.24%	94.91%	97.19%	97.92%	94.51%	97.20%	97.16%	97.82%
$\overrightarrow{\mathcal{EX}} - \overrightarrow{\mathcal{IM}}$	–93.01%	–86.06%	–85.01%	–89.67%	70.45%	84.73%	–89.53%	–90.27%

Notes: 1) the sample includes the EU countries and countries integrated with it, except Liechtenstein; 2) the convergence coefficient on the plane of Exports - Imports was calculated as the ratio of the length of the sum of countries' vectors to the sum of their lengths; 2) in the space of countries, all trade flows of a certain country are displayed on each coordinate axis; 3) convergence coefficients in the space of countries were calculated by two methods: by the sum method - as the ratio of the length of the sum of vectors of exports and imports of a certain product to the sum of their lengths and by the difference method - as the difference of the lengths of vectors of exports and imports of a certain product, divided by the length of their difference.
Source: prepared by the authors based on data from the WITS website

Appendix 4 presents coefficients of convergence of vectors of trade between Ukraine and the main geopolitical regions by individual groups of goods - capital, consumer, intermediate and final ones. The left part of the appendix presents the results of the study of vector convergence for 2021 and 2022 on the plane of Exports - Imports. The right part shows the results in the opposite sequence of mathematical operations - coefficients of convergence of export and import vectors on

[1] In view of this, further the proposed article presents the results of the study mainly using the vector difference method.

the plane of Trade flows 2021 - Trade flows 2022. In general, convergence coefficients were calculated using both alternative methods - the vector sum method and the vector difference method. However, this article presents an analysis of coefficients using the second method.

In general, in 2022, the export-import structure of Ukrainian trade changed little - the corresponding convergence coefficients were close to ± 100% (see the left part of Appendix 4). The same can be said about the differences in time structures of Ukrainian exports and Ukrainian imports (see the right part of Appendix 4). As noted in the previous section of the article, the proximity to zero of the convergence coefficient calculated by the difference method reflects the proximity of the norms of compared vectors, not their structures. This effect was most noticeable in trade in capital goods with Hungary and trade in consumer goods with the countries of the Middle East and North Africa (see the first and second columns of the left part of Appendix 4).

Coefficients of domestic trade with the vast majority of regions and countries were in the "red zone" - the volume of trade in 2022 decreased, and the two-year volume of imports exceeded the two-year volume of exports. In particular, positive difference in two-year volumes of exports and imports of intermediate goods in trade with the World, with the Europe & Central Asia region (including the EU+, Central Asia, the South Caucasus & Turkey country groups), with the Middle East & North Africa region (including Iran and Israel), with North America and with South Asia became the exception (see the last column of the right part of Appendix 4). It is worth noting separately the growth in trade in consumer goods with the EU+ group of countries, Turkey, Israel and South Asia (see the second column of the left part of Appendix 4).

Appendix 5 presents convergence coefficients characterising the degree of similarity of Ukrainian foreign trade in three groups of goods. The left part of the appendix presents the results of the study of the convergence of vectors of capital, consumer and intermediate goods on the plane of Exports - Imports. In this study, the only possible calculation method - the vector sum method - was applied. The right part of Appendix 5 presents the results of the study in the space of three products. In this coordinate system, relative length of the vector of exports and two pairs of mutually opposite convergence coefficients were calculated for each trading partner. The first such pair consisted of coefficients characterising the convergence of vectors of exports and imports of one year. The second pair of coefficients consisted of coefficients of exports and imports characterising the convergence of the corresponding vectors of two different years. The appendix presents convergence coefficients using the difference method.

In general, coefficients of convergence of three vectors of products were close to 100% and changed little in 2022 (see the left part of Appendix 5). Thus, for the Europe & Central Asia region (and in particular for the EU+ group), vector convergence coefficients on the plane of Exports - Imports decreased slightly. In the space of three products, this change was accompanied by a slight drop in relative length of the vector of exports. As for trade with individual European partners, it represented a rather motley picture. Thus, in trade with the Netherlands, the convergence of three vectors of products changed little, but in general (in the space of three products) the share of exports fell by one and a half times. The export-import structure of trade in three products with Italy and the United Kingdom substantially leveled off in 2022, but this was accompanied by a very strong drop in the share of total exports of three products.

Similar processes occurred in trade with Turkey, the Middle East & North Africa region (in particular with Iran and Israel) and South Asia. On the contrary, with almost the same convergence of vectors of products on the plane of Exports - Imports, the share of exports in the total trade of three products with Austria, Belgium and Hungary in 2022 increased significantly.

As for coefficients of vector convergence in the space of three products, they mostly also ended up in the "red zone" - in 2021 and 2022 the total volume of imports from most countries was greater than the total volume of exports to them, while in 2022 they both decreased (see four right columns of Appendix 5). Against this background, trade with Ukraine's closest neighbors - Moldova, Poland and Romania - stood out. Although Ukrainian exports to Moldova decreased, they remained larger than imports. All four coefficients of trade with Poland and Romania were positive.

Prospects for further investigations

The research presented in this article can be further developed in several directions. First, all convergence coefficients can be calculated not for absolute, but for relative values of trade flows. For this, the volumes of exports and imports should be previously normalised. Second, the two methods for calculating convergence coefficients considered above can be supplemented by at least one more.

The third possible method for calculating coefficients of foreign trade is based on the fact that the norm of the difference of two vectors is not greater than the norm of their sum. The ratio of these values will be the coefficient of vector divergence. It will be equal to one only if compared vectors are mutually perpendicular (that is, located on different coordinate axes). In this case, the parallelogram of compared vectors turns into a rectangle, its diagonals become equal. A geometric interpretation of this property is presented in Figure 5.

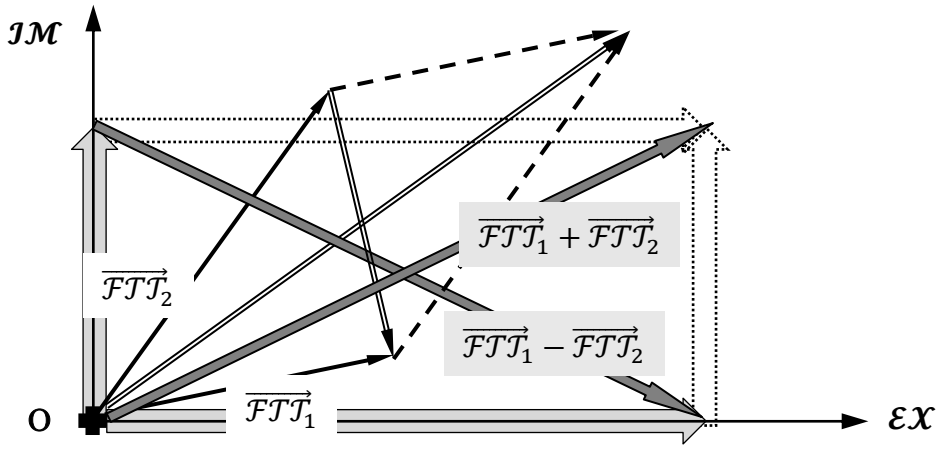

Figure 5. The method for calculating the coefficient of vector divergence on the plane of Exports - Imports

Source: I. Zagoruyiko's model

Unlike the vector difference method, this method can also be used when the norms of compared vectors are equal. However, it also has its own limitation. The further from unity the value of the divergence coefficient is, the less it reflects the difference in vector structures, and the more - the difference in their values. Thus, the divergence coefficient can be used as an additional tool for analysing foreign trade if the convergence coefficient is close to zero.

In two-dimensional space (on XOY plane), the coefficient of divergence of $\overrightarrow{OV_1}$, $\overrightarrow{OV_2}$ vectors will be calculated as

$$\mathbb{div}\left(\overrightarrow{OV_1}, \overrightarrow{OV_2}\right) = \frac{\left\|\overrightarrow{OV_1} - \overrightarrow{OV_2}\right\|}{\left\|\overrightarrow{OV_1} + \overrightarrow{OV_2}\right\|} \leq 1. \tag{31}$$

In the case of comparing three vectors, it is advisable to define the divergence coefficient as the mean of coefficients of three pairs of vectors

$$\mathbb{div}\left(\overrightarrow{OV_1}, \overrightarrow{OV_2}, \overrightarrow{OV_3}\right) = \frac{1}{3}\left(\frac{\left\|\overrightarrow{OV_1} - \overrightarrow{OV_2}\right\|}{\left\|\overrightarrow{OV_1} + \overrightarrow{OV_2}\right\|} + \frac{\left\|\overrightarrow{OV_2} - \overrightarrow{OV_3}\right\|}{\left\|\overrightarrow{OV_2} + \overrightarrow{OV_3}\right\|} + \frac{\left\|\overrightarrow{OV_3} - \overrightarrow{OV_1}\right\|}{\left\|\overrightarrow{OV_3} + \overrightarrow{OV_1}\right\|}\right). \tag{32}$$

The coefficient of divergence of three vectors in three-dimensional space is determined as the ratio of the mean length of minor diagonals of the parallelepiped formed by vectors to the length of its major diagonal

$$\mathbb{div}\left(\overrightarrow{OV_{1,2,3}}\right) = \frac{\left\|\overrightarrow{OV_1} + \overrightarrow{OV_2} - \overrightarrow{OV_3}\right\| + \left\|\overrightarrow{OV_1} + \overrightarrow{OV_3} - \overrightarrow{OV_2}\right\| + \left\|\overrightarrow{OV_3} + \overrightarrow{OV_2} - \overrightarrow{OV_1}\right\|}{3 \cdot \left\|\overrightarrow{OV_1} + \overrightarrow{OV_2} + \overrightarrow{OV_3}\right\|}. \tag{33}$$

As for the normalisation of trade flows, the choice of its method is determined by the purpose of the study.

Thus, if the purpose is to study the impact of foreign trade on the country's economy, then the values of exports and imports of a certain product should be converted into shares, respectively, in the national production of this product and in its domestic use:

$$\mathcal{EX}(p_\varrho) \Rightarrow \frac{\mathcal{EX}(p_\varrho)}{\mathcal{Q}(p_\varrho) + \mathcal{EX}(p_\varrho) - \mathcal{IM}(p_\varrho)}, \qquad \mathcal{IM}(p_\varrho) \Rightarrow \frac{\mathcal{IM}(p_\varrho)}{\mathcal{Q}(p_\varrho)}, \tag{34), (35}$$

where $\mathcal{Q}(p_\varrho)$ - the volume of internal use of the p_ϱ product.

If the purpose is to study the dependence of foreign trade on the flow of a certain product, then such normalisation is appropriate:

$$\mathcal{EX}_{\varsigma\tau}(p_\varrho) \Rightarrow \frac{\mathcal{EX}_{\varsigma\tau}(p_\varrho)}{\sum_i \mathcal{EX}_{\varsigma\tau}(p_i)}, \quad \mathcal{IM}_{\varsigma\tau}(p_\varrho) \Rightarrow \frac{\mathcal{IM}_{\varsigma\tau}(p_\varrho)}{\sum_i \mathcal{IM}_{\varsigma\tau}(p_i)}. \tag{36), (37}$$

The study of relative dependence on a certain trading partner should be carried out using the following normalised values:

$$\mathcal{EX}_{\varrho\tau}(C_\varsigma) \Rightarrow \frac{\mathcal{EX}_{\varrho\tau}(C_\varsigma)}{\sum_h \mathcal{EX}_{\varrho\tau}(C_h)}, \quad \mathcal{IM}_{\varrho\tau}(C_\varsigma) \Rightarrow \frac{\mathcal{IM}_{\varrho\tau}(C_\varsigma)}{\sum_h \mathcal{IM}_{\varrho\tau}(C_h)}. \tag{38), (39}$$

To study the dynamics of trade flows, the following normalisation can be used:

$$\mathcal{EX}_{\varsigma\varrho}(t_\tau) \Rightarrow \frac{\mathcal{EX}_{\varsigma\varrho}(t_\tau)}{\sum_j \mathcal{EX}_{\varsigma\varrho}(t_j)}, \quad \mathcal{IM}_{\varsigma\varrho}(t_\tau) \Rightarrow \frac{\mathcal{IM}_{\varsigma\varrho}(t_\tau)}{\sum_j \mathcal{IM}_{\varsigma\varrho}(t_j)}. \tag{40), (41}$$

The transition from the sums of $\mathcal{TF}$ trade flows of a certain type (exports or imports) to their vector norms

$$\sum_i \mathcal{TF}_{\varsigma\tau}(p_i) \Rightarrow \sqrt{\sum_i \mathcal{TF}^2_{\varsigma\tau}(p_i)}, \tag{42}$$

$$\sum_h \mathcal{TF}_{\varrho\tau}(C_h) \Rightarrow \sqrt{\sum_h \mathcal{TF}^2_{\varrho\tau}(C_h)}, \tag{43}$$

$$\sum_j \mathcal{TF}_{\varsigma\varrho}(t_j) \Rightarrow \sqrt{\sum_j \mathcal{TF}^2_{\varsigma\varrho}(t_j)} \tag{44}$$

makes it possible to analyse more complex structures and dependencies. In particular, it becomes possible to study trade with different countries and in different periods of time on the plane of Norm of the vector of product exports - Norm of the vector of product imports - $\left\|\overrightarrow{\mathcal{EX}(p)}\right\|, \left\|\overrightarrow{\mathcal{IM}(p)}\right\|$, in the space of norms of vectors of product flows directed to different countries in a t_τ year - $\left\|\overrightarrow{\mathcal{TF}(p)}(C_1, t_\tau)\right\|, \ldots \left\|\overrightarrow{\mathcal{TF}(p)}(C_H, t_\tau)\right\|$, in the space of norms of vectors of aggregate flows (flows to the entire set of countries) of certain products - $\left\|\overrightarrow{\mathcal{TF}(C)}(p_1, t_\tau)\right\|, \ldots \left\|\overrightarrow{\mathcal{TF}(C)}(p_I, t_\tau)\right\|$.

Potential implementation of results

The vector model, tested on Ukraine's foreign trade in 2021-2022, can also be used in other studies.

First, this model can be used to analyse other international economic flows - capital, human and information ones. International capital flows can be detailed by types and terms of assets, human flows - by professions, qualifications, demographic and ethnic characteristics, information flows - by the nature of content, method of distribution and types of addressees.

Second, the proposed model can serve as a tool for econometric research of different geopolitical dependencies and influences of certain countries, changes in their foreign economic policy.

The vector model of analysis is well consistent with the data convex hull approach (DEA - Data Envelopment Analysis). Thus, it can be applied when constructing international frontiers on the plane of Exports - Imports: frontiers of a certain country's foreign economic dependence and frontiers of its foreign economic partners' dependence on it.

Figure 6 shows foreign trade frontiers of $\mathcal{V}$ country and its partners. In the first case, each international flow of goods was divided into total volumes of exports or imports of $\mathcal{V}$ country. Thus, upper left and lower right parts of the convex hull of constructed states formed mutually opposite frontiers of $\mathcal{V}$ country's dependence on its trading partners. In the second case, all international flows of goods were divided into total volumes of imports or exports of $\mathcal{V}$ country's trading partners. In this case, upper left and lower right parts of constructed hall became mutually opposite frontiers of the dependence of other countries on $\mathcal{V}$ country. In both coordinate systems, the diagonal of the square connecting O origin of coordinates and A opposite state is the line of equivalent dependence of countries on exports and imports. If $\mathcal{V}$ country has the same number of export and import partners ($H_{\mathcal{EX}} = H_{\mathcal{IM}}$), then the state of ideal diversification of its foreign trade will be located on the line of equivalent dependence.

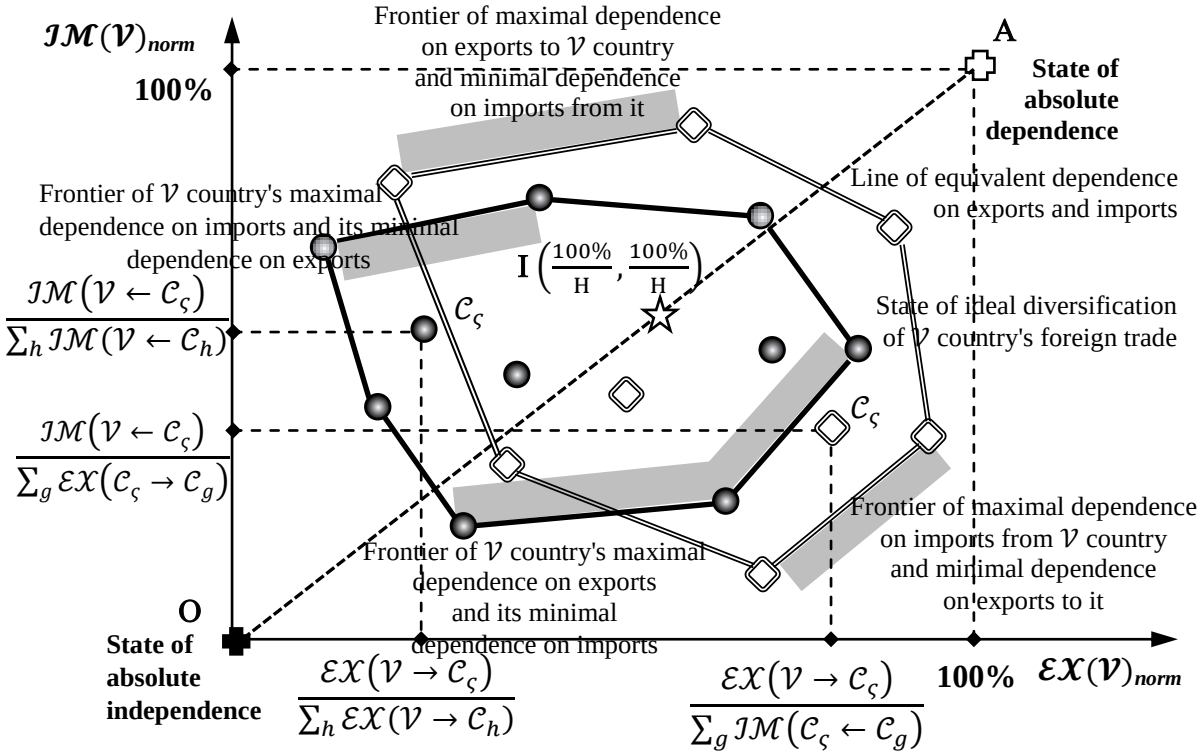

Figure 6. Frontiers of countries' dependence on the plane of Exports - Imports normalised according to their total volumes

Source: I. Zagoruyiko's model

It is advisable to carry out further analysis of international position of the country under study using the mutual dependence model. For this, the differences in the coordinates of the states shown in Figure 6 are chosen as new coordinates. Two alternative ways of such a representation are possible.

In the first system, the differences of the flows of the same name between $\mathcal{V}$ country and its trading partners will serve as the coordinates:

$$\delta\mathcal{EX}(\mathcal{V} \rightleftarrows \mathcal{C}_\varsigma)_{norm} = \frac{\mathcal{EX}(\mathcal{V} \rightarrow \mathcal{C}_\varsigma)}{\sum_h \mathcal{EX}(\mathcal{V} \rightarrow \mathcal{C}_h)} - \frac{\mathcal{EX}(\mathcal{C}_\varsigma \rightarrow \mathcal{V})}{\sum_g \mathcal{EX}(\mathcal{C}_\varsigma \rightarrow \mathcal{C}_g)}, \quad (45)$$

$$\delta\mathcal{IM}(\mathcal{V} \leftrightarrows \mathcal{C}_\varsigma)_{norm} = \frac{\mathcal{IM}(\mathcal{V} \leftarrow \mathcal{C}_\varsigma)}{\sum_h \mathcal{IM}(\mathcal{V} \leftarrow \mathcal{C}_h)} - \frac{\mathcal{IM}(\mathcal{C}_\varsigma \leftarrow \mathcal{V})}{\sum_g \mathcal{IM}(\mathcal{C}_\varsigma \leftarrow \mathcal{C}_g)}. \quad (46)$$

The second coordinate system will be formed by the differences of two normalisations of one flow of $\mathcal{V}$ country:

$$\delta\mathcal{FT}\left(\mathcal{V}\to\mathcal{C}_\varsigma\right)_{norm}=\frac{\mathcal{EX}\left(\mathcal{V}\to\mathcal{C}_\varsigma\right)}{\sum_h\mathcal{EX}\left(\mathcal{V}\to\mathcal{C}_h\right)}-\frac{\mathcal{IM}\left(\mathcal{C}_\varsigma\leftarrow\mathcal{V}\right)}{\sum_g\mathcal{IM}\left(\mathcal{C}_\varsigma\leftarrow\mathcal{C}_g\right)}, \quad (47)$$

$$\delta\mathcal{FT}\left(\mathcal{V}\leftarrow\mathcal{C}_\varsigma\right)_{norm}=\frac{\mathcal{IM}\left(\mathcal{V}\leftarrow\mathcal{C}_\varsigma\right)}{\sum_h\mathcal{IM}\left(\mathcal{V}\leftarrow\mathcal{C}_h\right)}-\frac{\mathcal{EX}\left(\mathcal{C}_\varsigma\to\mathcal{V}\right)}{\sum_g\mathcal{EX}\left(\mathcal{C}_\varsigma\to\mathcal{C}_g\right)}, \quad (48)$$

where $\mathcal{TF}\left(\mathcal{V}\to\mathcal{C}_\varsigma\right)$ - the flow of goods from $\mathcal{V}$ country to $\mathcal{C}_\varsigma$ country, and $\mathcal{TF}\left(\mathcal{V}\leftarrow\mathcal{C}_\varsigma\right)$ - the flow of these goods in the opposite direction.

The first coordinate system reflects the attitude of $\mathcal{V}$ country towards other countries as players in the global market. In such a system, $\mathcal{V}$ country is interested in comparing its own export policy with the export policy of other countries, and its own import diversification with the import diversification of other countries. The second coordinate system reflects the attitude to other countries as objects of influence or the transformation of $\mathcal{V}$ country itself into such an object. In such a system, $\mathcal{V}$ country analyses foreign trade from the point of view of reducing dependence on its counterparties and increasing its own influence on them.

Figure 7 shows the case when $\mathcal{V}$ country has more influence on its trading partners than they have on it.

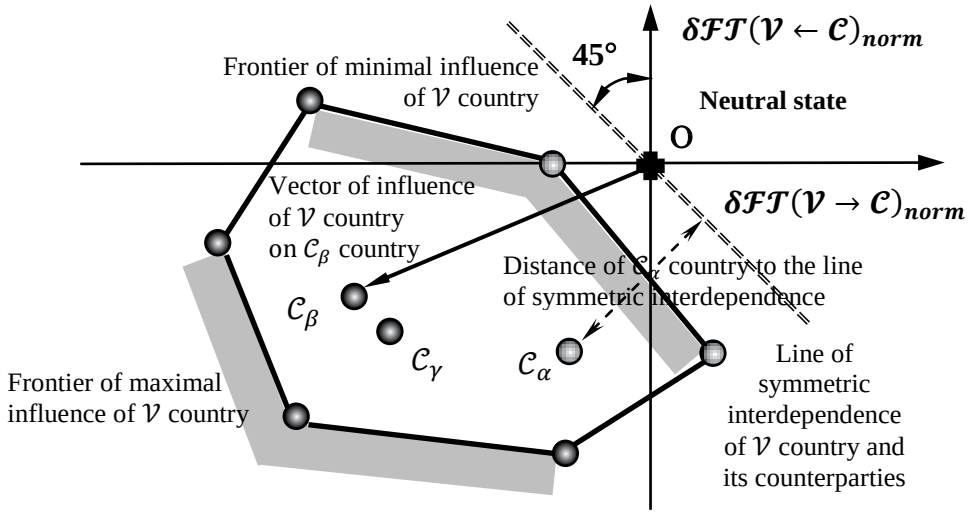

Figure 7. Frontiers of a country's foreign trade influence on the plane of differences between two normalisations of one flow

Source: I. Zagoruyiko's model

Similarly, the multi-product model of trade between two countries is constructed. In the system of the second type, the coordinate axes will display the values:

$$\delta\mathcal{TF}\left(\mathcal{U}\to\mathcal{W},p_\varrho\right)_{norm}=\frac{\mathcal{EX}\left(\mathcal{U}\to\mathcal{W},p_\varrho\right)}{\sum_h\mathcal{EX}\left(\mathcal{U}\to\mathcal{C}_h,p_\varrho\right)}-\frac{\mathcal{IM}\left(\mathcal{W}\leftarrow\mathcal{U},p_\varrho\right)}{\sum_g\mathcal{IM}\left(\mathcal{W}\leftarrow\mathcal{C}_g,p_\varrho\right)}, \quad (49)$$

$$\delta\mathcal{TF}\left(\mathcal{U}\leftarrow\mathcal{W},p_\varrho\right)_{norm}=\frac{\mathcal{IM}\left(\mathcal{U}\leftarrow\mathcal{W},p_\varrho\right)}{\sum_h\mathcal{IM}\left(\mathcal{U}\leftarrow\mathcal{C}_h,p_\varrho\right)}-\frac{\mathcal{EX}\left(\mathcal{W}\to\mathcal{U},p_\varrho\right)}{\sum_g\mathcal{EX}\left(\mathcal{W}\to\mathcal{C}_g,p_\varrho\right)}, \quad (50)$$

where $\mathcal{TF}\left(\mathcal{U}\to\mathcal{W},p_\varrho\right)$ - the flow of goods of p_ϱ group from $\mathcal{U}$ country to $\mathcal{W}$ country, and $\mathcal{TF}\left(\mathcal{U}\leftarrow\mathcal{W},p_\varrho\right)$ - the flow of these goods in the opposite direction.

Figure 8 shows the case when $\mathcal{U}$ country is completely dependent on $\mathcal{W}$ country.

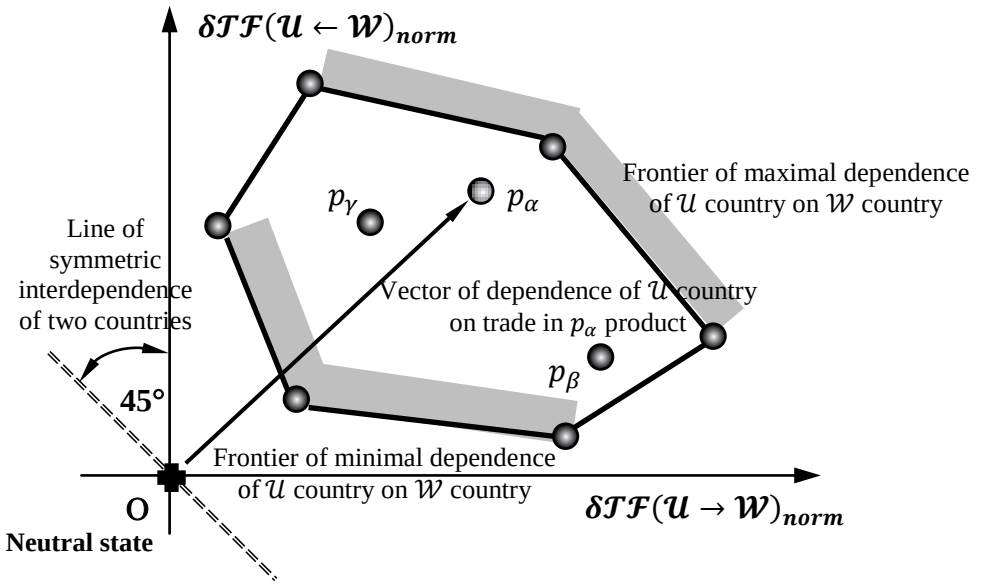

Figure 8. Frontiers of dependence of $\mathcal{U}$ country on $\mathcal{W}$ country in the multi-product trade model
Source: I. Zagoruyiko's model

In all coordinate systems considered above, foreign trade flows can be normalised in another way:

$$\mathcal{EX}(\mathcal{V} \rightarrow \mathcal{C}_\varsigma)_{norm} = \frac{\mathcal{EX}(\mathcal{V} \rightarrow \mathcal{C}_\varsigma)}{\mathcal{Y}(\mathcal{V})}, \qquad \mathcal{EX}(\mathcal{C}_\varsigma \rightarrow \mathcal{V})_{norm} = \frac{\mathcal{EX}(\mathcal{C}_\varsigma \rightarrow \mathcal{V})}{\mathcal{Y}(\mathcal{C}_\varsigma)}, \qquad (51), (52)$$

$$\mathcal{IM}(\mathcal{V} \leftarrow \mathcal{C}_\varsigma)_{norm} = \frac{\mathcal{IM}(\mathcal{V} \leftarrow \mathcal{C}_\varsigma)}{\mathcal{Y}(\mathcal{V}) - \mathcal{NX}(\mathcal{V})}, \quad \mathcal{IM}(\mathcal{C}_\varsigma \leftarrow \mathcal{V})_{norm} = \frac{\mathcal{IM}(\mathcal{C}_\varsigma \leftarrow \mathcal{V})}{\mathcal{Y}(\mathcal{C}_\varsigma) - \mathcal{NX}(\mathcal{C}_\varsigma)}, \qquad (53), (54)$$

where $\mathcal{Y}$ - gross domestic product, $\mathcal{NX}$ - net exports of goods. Thus, the first two values show what share of its gross product the country sells to a certain trading partner. The second two values show what share of domestic use of goods is made up of those purchased by residents from a certain trading partner. This method of normalisation is appropriate when foreign trade is considered in a broader, macroeconomic context. In particular, this method of normalisation should be used in analysing the effectiveness of sanctions policy.

The sums of international flows of one country normalised according to its GDP and domestic use of products can be considered as new coordinates. In this coordinate system, the sum of macroeconomically normalised flows of $\mathcal{V}$ country is the abscissa, and the similar sum of flows of its $\mathcal{C}$ trading partner is the ordinate:

$$\sigma\mathcal{TF}(\mathcal{V} \rightleftarrows \mathcal{C}_\varsigma)_{norm} = \frac{\mathcal{EX}(\mathcal{V} \rightarrow \mathcal{C}_\varsigma)}{\mathcal{Y}(\mathcal{V})} + \frac{\mathcal{IM}(\mathcal{V} \leftarrow \mathcal{C}_\varsigma)}{\mathcal{Y}(\mathcal{V}) - \mathcal{NX}(\mathcal{V})}, \qquad (55)$$

$$\sigma\mathcal{TF}(\mathcal{C}_\varsigma \leftrightarrows \mathcal{V})_{norm} = \frac{\mathcal{EX}(\mathcal{C}_\varsigma \rightarrow \mathcal{V})}{\mathcal{Y}(\mathcal{C}_\varsigma)} + \frac{\mathcal{IM}(\mathcal{C}_\varsigma \leftarrow \mathcal{V})}{\mathcal{Y}(\mathcal{C}_\varsigma) - \mathcal{NX}(\mathcal{C}_\varsigma)}. \qquad (56)$$

The use of such a coordinate system creates another DEA model, geometrically different from those considered above (see Figure 9). In the situation shown in Figure 9, the state of double extremum is located in the area of predominant influence of other countries on $\mathcal{V}$ country.

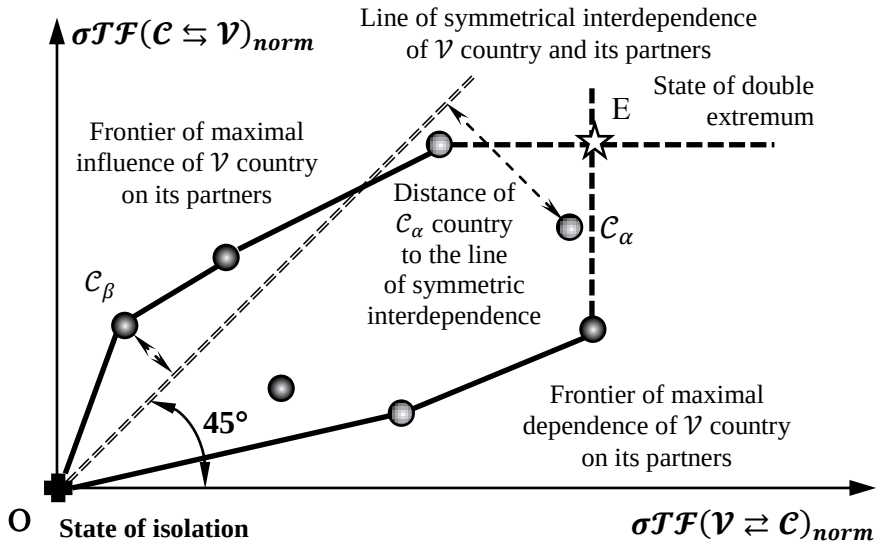

Figure 9. International frontiers of the country on the plane of the sums of macroeconomically normalised flows of exports and imports

Source: I. Zagoruyiko's model

By replacing scalar coordinates with norms of macroeconomic vectors of trade turnover

$$\left\|\overrightarrow{\mathcal{FTT}(\mathcal{V})}_{norm}\right\| = \sqrt{\mathcal{EX}^2(\mathcal{V} \to \mathcal{C})_{norm} + \mathcal{IM}^2(\mathcal{V} \leftarrow \mathcal{C})_{norm}}, \quad (57)$$

$$\left\|\overrightarrow{\mathcal{FTT}(\mathcal{C})}_{norm}\right\| = \sqrt{\mathcal{EX}^2(\mathcal{C} \to \mathcal{V})_{norm} + \mathcal{IM}^2(\mathcal{C} \leftarrow \mathcal{V})_{norm}}, \quad (58)$$

a new modified model is formed. Such a model is appropriate when $\mathcal{V}$ country does not exclude the possibility of a complete break in its foreign trade relations.

In models built on the planes of differences ($\delta\mathcal{TF}$) or sums ($\sigma\mathcal{TF}$) of trade flows, it is possible to determine the total dependence of $\mathcal{V}$ country on its partners. According to the scalar approach, the total dependence of the country under study will be determined as the algebraic sum of the distances of its trading partners to the line of symmetric interdependence. On the plane of differences of flows ($\delta\mathcal{TF}$), the sum of the distances of states located below this line is subtracted from the sum of the distances of higher states. On the plane of sums of flows ($\sigma\mathcal{TF}$), the sum of the distances of states located above this line is subtracted from the sum of the distances of lower states. The total influence of the country will be equal to the negative value of its total dependence.

From a geopolitical point of view, the scalar approach reflects a "softer" strategy of $\mathcal{V}$ country, since the set of symmetric states is the basis for assessing the influence. The vector approach reflects a "harder" strategy, since in this case O origin of the coordinates is the basis for assessing. It can be implemented in two versions - by calculating the norm of vector sums and by calculating the sum of vector norms. At the same time, it is necessary to take into account that states located in different quadrants or on different sides of the line of symmetric interdependence are qualitatively opposite. This difference can be taken into account using the method of conventional complex coordinates. The essence of the proposed method is as follows. On the plane of differences of flows ($\delta\mathcal{TF}$), the coordinate of states in the II and IV quadrants with a smaller modulus is multiplied by i imaginary unit ($i^2 = -1$). The vector norm of such a state will be calculated as

$$|x(\mathcal{C}_\varsigma)| > |y(\mathcal{C}_\varsigma)| \implies \|x(\mathcal{C}_\varsigma), iy(\mathcal{C}_\varsigma)\| = \sqrt{x^2(\mathcal{C}_\varsigma) - y^2(\mathcal{C}_\varsigma)}, \quad (59)$$

$$|x(\mathcal{C}_\varsigma)| < |y(\mathcal{C}_\varsigma)| \implies \|ix(\mathcal{C}_\varsigma), y(\mathcal{C}_\varsigma)\| = \sqrt{y^2(\mathcal{C}_\varsigma) - x^2(\mathcal{C}_\varsigma)}. \quad (60)$$

On the plane of sums of flows ($\sigma\mathcal{TF}$), the smaller coordinate is multiplied by an imaginary unit. A visualisation of this method is presented in Figure 10.

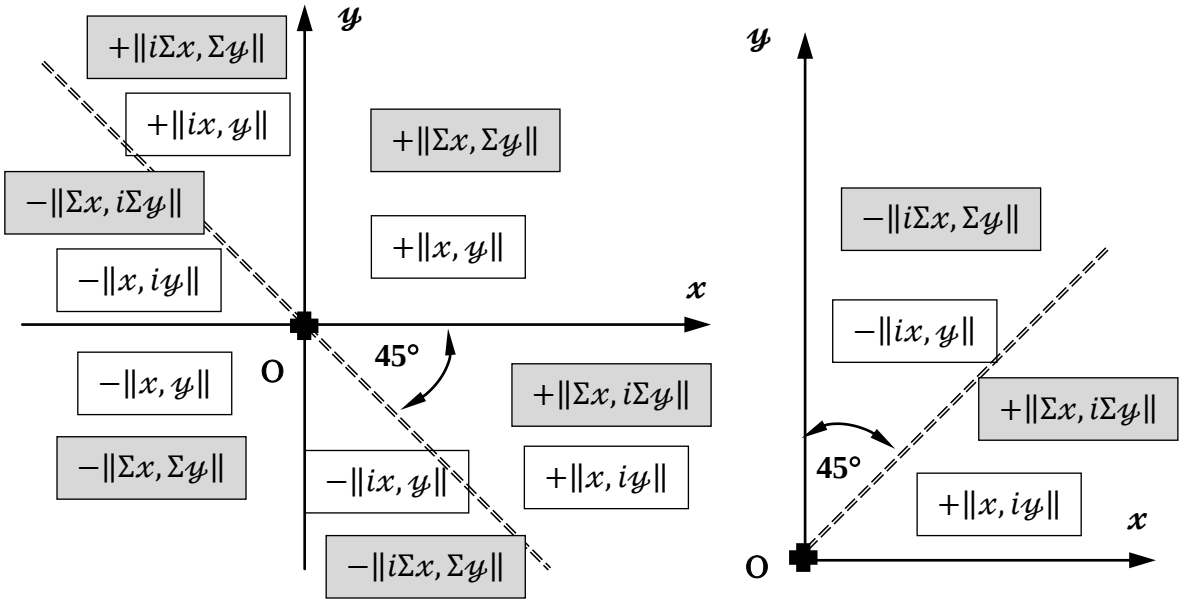

Figure 10. Determination of algebraic signs when calculating vector norms by the method of conventional complex coordinates: the left part - the plane of differences of flows ($\delta\mathcal{TF}$), the right part - the plane of sums of flows ($\sigma\mathcal{TF}$)

Source: I. Zagoruyiko's model

Using the method of conventional complex coordinates, it is possible to determine the geopolitical position of a certain country relative to the frontiers of $\mathcal{V}$ country's influence. To do this, the state of this country is projected onto the opposite international frontiers of $\mathcal{V}$ country along the perpendicular to the line of symmetric interdependence. The geopolitical position of a trading partner will be determined as the norm of the sum of projection vectors or as the sum of the norms of these vectors. A visualisation of the application of this method in DEA models is presented in Figure 11.

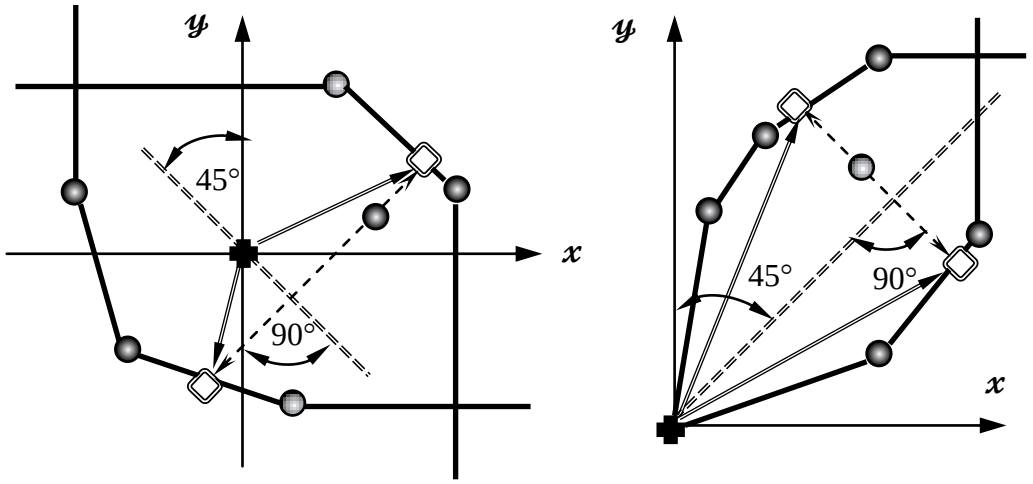

Figure 11. Determination of the geopolitical position of the country relative to the frontiers of $\mathcal{V}$ country's influence: the left part - the plane of differences of flows ($\delta\mathcal{TF}$), the right part - the plane of sums of flows ($\sigma\mathcal{TF}$)

Source: I. Zagoruyiko's model

Conclusions

Vector analysis of the state of Ukrainian foreign trade in 2021-2022 makes it possible to draw certain conclusions.

First, a comparative analysis of scalar and vector models has revealed that the specific weight of Ukrainian exports in 2022 was strongly correlated with the similar indicator in 2021. All regression equations showed a positive relationship between these indicators. Quadratic equations described this relationship better than linear ones. The R^2 coefficient of determination was especially high in the case of consumer and final goods on the plane of Exports - Imports and in the space of three products. However, all coefficients of determination of the vector model were smaller than the corresponding coefficients of the scalar model. This gives reason to believe that in other studies the vector model will also constitute the lower bound of the correlation-regression relationship.

Second, a comparison of relative indicators of the volume of domestic foreign trade calculated on the basis of two models has shown that the discrepancy between them does not exceed 5% and in many cases amounts to several hundredths of a percent. At the same time, identified discrepancies did not violate the order of the countries in the ranked series. According to the authors, this fact is an argument for the feasibility of joint application of both models.

Third, the calculation and interpretation of coefficients of convergence of domestic foreign trade vectors have shown the effectiveness of the vector model of data analysis. Thus, convergence coefficients characterising the geographical similarity of the structure of trade with the EU+ countries showed the importance of trade in intermediate goods as a factor in financial stability of the national economy. Coefficients of domestic trade with the vast majority of regions and countries were in the “red zone” - the volume of trade in 2022 decreased, and two-year volume of imports exceeded two-year volume of exports. At the same time, the export-import structure of Ukrainian trade changed little - the corresponding convergence coefficients were close to ± 100%.

According to the authors, the proposed vector model can serve as a tool in a wide range of international research, primarily of a geopolitical nature.

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None.

Conflict of interest

None.

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Appendix 1

Relative indicators of the volume of Ukraine's foreign trade in capital goods in 2021-2022

Region/Country	2021				2022			
	% in the volume of trade in capital goods in two years		% in the volume of trade in three groups of goods in 2021		% in the volume of trade in capital goods in two years		% in the volume of trade in three groups of goods in 2022	
	scalar model	vector model	scalar model	vector model	scalar model	vector model	scalar model	vector model
Europe & CA	60.90%	61.05%	16.50%	17.36%	39.10%	38.95%	14.17%	14.66%
Aggressors	86.95%	86.82%	13.64%	12.39%	13.05%	13.18%	8.82%	7.48%
EU+	58.11%	59.29%	17.90%	19.82%	41.89%	40.71%	14.68%	15.45%
Austria	61.41%	62.59%	17.97%	2.24%	38.59%	37.41%	15.34%	18.13%
Czech Republic	55.65%	56.50%	24.99%	28.69%	44.35%	43.50%	23.35%	26.35%
France	57.11%	56.59%	19.49%	21.58%	42.89%	43.41%	21.18%	24.07%
Germany	61.24%	62.24%	30.86%	34.37%	38.76%	37.76%	24.71%	27.31%
Hungary	52.05%	50.30%	17.06%	17.12%	47.95%	49.70%	18.59%	19.59%
Italy	61.55%	61.77%	17.09%	18.65%	38.45%	38.23%	19.87%	22.52%
Netherlands	52.78%	50.86%	12.75%	12.04%	47.22%	49.14%	13.67%	13.93%
Poland	51.51%	53.21%	13.30%	14.49%	48.49%	46.79%	11.33%	11.35%
Romania	52.75%	53.30%	10.99%	11.68%	47.25%	46.70%	6.65%	6.55%
Slovakia	63.30%	65.08%	17.32%	20.25%	36.70%	34.92%	9.54%	10.46%
Sweden	70.67%	70.88%	52.38%	57.41%	29.33%	29.12%	30.27%	33.16%
UK	60.63%	61.87%	17.81%	20.15%	39.37%	38.13%	19.64%	21.92%
Turkey	51.28%	53.85%	12.98%	14.25%	48.72%	46.15%	14.39%	14.38%
EA & Pacific	57.12%	56.41%	36.91%	39.82%	42.88%	43.59%	39.85%	42.47%
ME & N. Africa	63.38%	63.77%	5.78%	5.17%	36.62%	36.23%	5.50%	5.19%
North America	62.28%	62.06%	23.36%	24.62%	37.72%	37.94%	23.50%	25.91%
South Asia	59.64%	57.34%	6.84%	5.32%	40.36%	42.66%	6.30%	5.33%
World	59.66%	59.25%	19.22%	20.73%	40.34%	40.75%	18.23%	19.80%

Notes: 1) in the scalar model, the sum of exports and imports is used as the volume of foreign trade; 2) in the vector model, the length of the vector of flows on the plane of Exports - Imports is used as the volume of foreign trade; 3) EA - East Asia, CA - Central Asia, EU+ - the EU and countries integrated with it (excluding Liechtenstein), UK - United Kingdom, ME & N. Africa - Middle East & North Africa; 4) in the Europe & CA group, data are provided for countries with which the volume of trade in capital goods in 2021 exceeded USD 200 million.
Source: prepared by the authors based on data from the WITS website

Appendix 2

Relative indicators of the volume of Ukraine's foreign trade in consumer goods in 2021-2022

Region/Country	2021				2022			
	% in the volume of trade in consumer goods in two years		% in the volume of trade in three groups of goods in 2021		% in the volume of trade in consumer goods in two years		% in the volume of trade in three groups of goods in 2022	
	scalar model	vector model	scalar model	vector model	scalar model	vector model	scalar model	vector model
Europe & CA	53.34%	53.09%	42.78%	43.82%	46.66%	46.91%	50.07%	51.22%
Aggressors	77.55%	76.16%	43.94%	49.00%	22.45%	23.84%	54.80%	60.96%
EU+	49.71%	49.39%	43.56%	43.38%	50.29%	50.61%	50.12%	50.49%
Austria	59.03%	60.70%	51.00%	50.97%	40.97%	39.30%	48.10%	47.11%
Czech Republic	51.09%	51.47%	50.59%	49.03%	48.91%	48.53%	56.78%	55.13%
France	57.30%	58.46%	42.45%	44.31%	42.70%	41.54%	45.76%	45.79%
Germany	52.23%	52.49%	46.45%	44.18%	47.77%	47.51%	53.74%	52.37%
Hungary	57.55%	57.64%	58.97%	58.77%	42.45%	42.36%	51.47%	50.04%
Italy	55.88%	57.07%	26.71%	26.85%	44.12%	42.93%	39.24%	39.41%
Lithuania	41.62%	40.86%	54.36%	58.17%	58.38%	59.14%	70.18%	73.07%
Moldova	51.45%	53.67%	49.81%	51.34%	48.55%	46.33%	46.46%	45.23%
Netherlands	43.25%	42.38%	30.04%	28.56%	56.75%	57.62%	47.26%	46.51%
Poland	46.37%	45.66%	40.39%	39.71%	53.63%	54.34%	42.25%	42.12%
Romania	40.19%	39.16%	47.63%	44.75%	59.81%	60.84%	47.91%	44.51%
Slovakia	47.11%	46.70%	48.48%	48.38%	52.89%	53.30%	51.69%	53.12%
Region/Country	2021				2022			
	% in the volume of trade in consumer goods in two years		% in the volume of trade in three groups of goods in 2021		% in the volume of trade in consumer goods in two years		% in the volume of trade in three groups of goods in 2022	
	scalar model	vector model	scalar model	vector model	scalar model	vector model	scalar model	vector model
Spain	59.32%	59.76%	29.89%	31.65%	40.68%	40.24%	30.34%	32.29%
Switzerland	59.37%	59.62%	74.45%	77.83%	40.63%	40.38%	82.02%	84.66%
UK	57.30%	57.13%	46.11%	43.82%	42.70%	42.87%	58.34%	58.02%
Kazakhstan	52.29%	51.35%	56.84%	52.64%	47.71%	48.65%	68.83%	65.93%
Turkey	42.91%	42.98%	26.41%	29.68%	57.09%	57.02%	41.00%	46.36%
EA & Pacific	58.55%	58.06%	33.84%	36.56%	41.45%	41.94%	34.46%	36.46%
ME & N. Africa	49.17%	50.11%	25.29%	23.36%	50.83%	49.89%	43.09%	41.14%
North America	61.80%	63.09%	43.02%	42.85%	38.20%	36.91%	44.16%	43.15%
South Asia	33.79%	33.06%	20.77%	21.88%	66.21%	66.94%	55.38%	59.60%
World	53.82%	53.42%	39.10%	39.81%	46.18%	46.58%	47.04%	48.19%

Notes: 1) in the scalar model, the sum of exports and imports is used as the volume of foreign trade; 2) in the vector model, the length of the vector of flows on the plane of Exports - Imports is used as the volume of foreign trade; 3) EA - East Asia, CA - Central Asia, EU+ - the EU and countries integrated with it (excluding Liechtenstein), UK - United Kingdom, ME & N. Africa - Middle East & North Africa; 4) in the Europe & CA group, data are provided for countries with which the volume of trade in consumer goods in 2021 exceeded USD 400 million.
Source: prepared by the authors based on data from the WITS website

Appendix 3

Relative indicators of the volume of Ukraine's foreign trade in intermediate goods in 2021-2022

Region/Country	2021				2022			
	% in the volume of trade in intermediate goods in two years		% in the volume of trade in three groups of goods in 2021		% in the volume of trade in intermediate goods in two years		% in the volume of trade in three groups of goods in 2022	
	scalar model	vector model	scalar model	vector model	scalar model	vector model	scalar model	vector model
Europe & CA	60.38%	60.08%	40.72%	38.81%	39.62%	39.92%	35.75%	34.12%
Aggressors	83.40%	82.94%	42.43%	38.61%	16.60%	17.06%	36.38%	31.56%
EU+	55.46%	55.10%	38.54%	36.80%	44.54%	44.90%	35.20%	34.06%
Bulgaria	45.48%	43.53%	63.08%	64.54%	54.52%	56.47%	43.88%	44.05%
France	62.48%	62.21%	38.06%	34.11%	37.52%	37.79%	33.06%	30.14%
Germany	57.12%	58.03%	22.69%	21.45%	42.88%	41.97%	21.55%	20.32%
Hungary	48.65%	47.90%	23.97%	24.11%	51.35%	52.10%	29.94%	30.37%
Italy	71.89%	73.64%	56.20%	54.50%	28.11%	26.36%	40.89%	38.07%
Lithuania	58.55%	57.23%	36.62%	33.59%	41.45%	42.77%	23.86%	21.79%
Netherlands	63.71%	64.27%	57.21%	59.41%	36.29%	35.73%	39.07%	39.56%
Poland	47.43%	46.73%	46.31%	45.80%	52.57%	53.27%	46.42%	46.53%
Romania	38.09%	36.30%	41.38%	43.57%	61.91%	63.70%	45.45%	48.94%
Spain	60.93%	62.02%	58.94%	56.35%	39.07%	37.98%	55.92%	52.28%
UK	73.55%	76.01%	36.08%	36.03%	26.45%	23.99%	22.03%	20.06%
Turkey	61.32%	62.71%	60.61%	56.07%	38.68%	37.29%	44.61%	39.26%
EA & Pacific	62.09%	60.73%	29.25%	23.61%	37.91%	39.27%	25.69%	21.08%
ME & N. Africa	68.85%	70.21%	68.93%	71.48%	31.15%	29.79%	51.40%	53.66%
North America	63.33%	64.42%	33.62%	32.53%	36.67%	35.58%	32.34%	30.94%
South Asia	72.00%	73.63%	72.39%	72.79%	28.00%	26.37%	38.32%	35.07%
World	62.72%	63.12%	41.67%	39.45%	37.28%	36.88%	34.74%	32.01%

Notes: 1) in the scalar model, the sum of exports and imports is used as the volume of foreign trade; 2) in the vector model, the length of the vector of flows on the plane of Exports - Imports is used as the volume of foreign trade; 3) EA - East Asia, CA - Central Asia, EU+ - the EU and countries integrated with it (excluding Liechtenstein), UK - United Kingdom, ME & N. Africa - Middle East & North Africa; 4) in the Europe & CA group, data are provided for countries with which the volume of trade in intermediate goods in 2021 exceeded USD 600 million.
Source: prepared by the authors based on data from the WITS website

Appendix 4

Coefficients of convergence of Ukraine's foreign trade vectors by individual groups of goods in 2021-2022

Region/Country	Plane of Exports - Imports				Plane of Trade flows 2021 - Trade flows 2022			
	Coefficient of vector convergence 2021 and 2022 (by the difference method)				Coefficient of convergence of export and import vectors (by the difference method)			
	Capital goods	Consumer goods	Final goods	Inter-mediate goods	Capital goods	Consumer goods	Final goods	Inter-mediate goods
Europe & CA	–99.96%	–98.53%	–99.87%	–99.18%	–99.99%	–99.95%	–99.99%	99.34%
Aggressors	–99.54%	–99.68%	–99.20%	–99.42%	83.42%	–99.63%	–99.19%	–91.16%
EU+	–97.81%	62.34%	–99.09%	–97.22%	–99.43%	–99.89%	–99.99%	99.55%
Austria	–99.31%	–93.00%	–95.44%	–45.39%	–99.50%	–97.23%	–98.27%	16.53%
Belgium	–88.51%	–96.81%	–97.49%	–65.43%	–99.79%	–99.40%	–99.76%	–90.08%
Bulgaria	–87.86%	98.57%	98.21%	91.51%	–97.69%	–98.23%	–98.04%	98.63%
Czech Republic	–98.46%	–80.00%	–90.88%	–99.36%	–99.75%	–99.71%	–99.63%	98.14%
Denmark	69.02%	–98.70%	–95.41%	–68.90%	–99.18%	99.72%	94.43%	–60.71%
Finland	–99.69%	70.31%	–85.70%	–96.27%	–99.89%	–99.51%	–99.47%	–98.93%
France	–99.46%	–96.99%	–99.01%	–98.60%	–99.91%	–99.34%	–99.81%	–95.13%
Germany	–99.38%	–97.04%	–97.26%	–95.16%	–99.67%	–99.93%	–99.65%	–98.67%
Greece	–98.87%	99.77%	99.76%	–98.78%	–98.02%	–99.43%	–99.53%	57.15%
Hungary	–5.06%	–85.27%	–73.64%	56.32%	90.15%	–46.24%	27.96%	96.44%
Ireland	–30.15%	–100.0%	–99.96%	–95.12%	–99.43%	–100.0%	–99.98%	–96.80%
Italy	–99.98%	–97.38%	–99.05%	–99.06%	–99.97%	–99.51%	–99.66%	99.07%
Latvia	–62.52%	36.21%	37.65%	–49.92%	–48.58%	74.55%	81.13%	70.09%
Lithuania	–100.0%	99.21%	97.64%	–48.90%	–100.0%	–99.79%	–99.57%	6.44%
Moldova	–99,99%	–79,24%	–91,93%	98,08%	99,99%	98,27%	98,71%	99,62%
Netherlands	–21.86%	97.08%	91.63%	–99.78%	–97.56%	–99.44%	–99.09%	99.89%
Poland	–69.03%	91.10%	98.07%	87.07%	–98.19%	–99.18%	–99.94%	99.30%
Romania	–95.26%	71.33%	75.31%	97.65%	–99.82%	–65.03%	–79.92%	98.80%
Slovakia	–98.56%	96.50%	–82.42%	89.05%	–98.99%	–99.86%	–99.95%	93.23%
Slovenia	–99.90%	–95.38%	–96.65%	–61.07%	–99.99%	–99.75%	–99.82%	–65.43%
Spain	–98.83%	–99.81%	–99.97%	–98.15%	–99.90%	–99.93%	–99.99%	99.24%
Sweden	–99.99%	95.01%	–99.54%	–25.67%	–99.97%	–99.59%	–99.82%	–97.25%
Switzerland	–99.96%	–99.96%	–99.96%	–99.70%	–99.88%	–99.96%	–99.95%	–99.52%
UK	–99.11%	–99.87%	–99.86%	–96.07%	–99.47%	–99.98%	–99.97%	96.08%
CA, SC & T	–97.64%	48.22%	26.50%	–96.29%	–99.69%	–94.56%	–96.57%	96.92%
Azerbaijan	–45.89%	–99.67%	–99.95%	–83.73%	91.83%	99.67%	99.96%	82.38%
Georgia	–86.81%	–99.27%	–99.96%	–100.0%	93.80%	99.57%	99.98%	100.0%
Kazakhstan	–99.85%	–33.33%	–60.03%	–99.79%	99.97%	–94.30%	–50.59%	–99.84%
Turkey	–74.67%	99.99%	97.97%	–96.24%	–97.74%	–100.0%	–99.80%	98.08%
Uzbekistan	–99.99%	–100.0%	–99.99%	–92.26%	99.98%	100.00%	99.99%	–72.61%
EA & Pacific	–99.26%	–99.77%	–99.56%	–78.40%	–99.74%	–99.88%	–99.81%	–46.23%
ME & NA	–82.86%	–0.81%	–15.87%	–99.21%	63.10%	20.01%	26.44%	99.35%
Iran	97.74%	–99.28%	–50.92%	–75.38%	98.14%	–98.40%	–33.00%	64.02%
Israel	–97.18%	63.92%	58.74%	–99.57%	–92.29%	–63.47%	–62.24%	99.54%
North America	–99.97%	–98.70%	–99.55%	–99.07%	–99.98%	–99.39%	–99.78%	99.51%
South Asia	–58.94%	99.88%	97.48%	–99.45%	–59.74%	–99.51%	–97.44%	99.27%
World	–99.77%	–97.62%	–99.37%	–99.30%	–99.94%	–99.91%	–99.95%	99.37%

Notes: 1) CA - Central Asia, EA - East Asia, CA, SC & T - Central Asia, South Caucasus & Turkey, EU+ - the EU and countries integrated with it (excluding Liechtenstein), UK - United Kingdom, ME & NA - Middle East & North Africa; 2) the Europe & CA group provides data on countries for which the volumes of total domestic exports or imports in 2021 exceeded USD 200 million; 3) when calculating the convergence coefficient on the plane of Exports - Imports, the vector of 2021 was subtracted from the vector of 2022; 4) when calculating the convergence coefficient on the plane of Trade flows 2021 - Trade flows 2022, the vector of imports was subtracted from the vector of exports.

Source: prepared by the authors based on data from the WITS website

Appendix 5

Coefficients of convergence of Ukrainian foreign trade vectors for a set of three groups of goods in 2021-2022

Region/Country	Plane of Exports - Imports		Plane of Capital goods - Consumer goods - Intermediate goods					
	Coefficient of convergence of product vectors (by the sum method)		Relative length of export vector		Coefficient of convergence of export and import vectors (by the difference method)		Coefficient of convergence of vectors in 2021 and 2022 (by the difference method)	
	2021	2022	2021	2022	2021	2022	Exports	Imports
Europe & CA	94.98%	94.32%	42.57%	39.28%	–41.86%	–53.43%	–97.39%	–79.61%
Aggressors	95.82%	97.30%	32.88%	20.05%	–71.97%	–86.54%	–99.92%	–99.48%
EU+	93.96%	93.77%	42.99%	40.74%	–38.29%	–47.43%	–93.62%	–31.14%
Austria	97.52%	95.59%	29.54%	42.17%	–86.64%	–51.12%	65.30%	–99.78%
Belgium	99.57%	98.43%	25.40%	35.41%	–98.02%	–85.72%	58.94%	–95.56%
Bulgaria	89.53%	79.60%	66.73%	45.42%	63.16%	–14.82%	99.86%	94.25%
Czech Republic	96.58%	97.08%	32.98%	34.32%	–80.39%	–84.19%	–44.57%	–81.55%
Denmark	95.62%	94.12%	56.73%	56.15%	45.65%	35.66%	–91.96%	–61.05%
Finland	99.90%	99.83%	21.57%	14.62%	–99.48%	–99.20%	–94.64%	–75.33%
France	97.39%	98.41%	30.76%	29.11%	–81.19%	–89.82%	–86.91%	–98.96%
Germany	99.20%	99.28%	24.66%	28.53%	–94.02%	–95.67%	–89.70%	–81.56%
Greece	94.54%	97.14%	28.13%	7.09%	–72.72%	–95.95%	–95.29%	92.42%
Hungary	99.02%	99.07%	47.17%	57.88%	–44.33%	77.67%	–13.54%	–96.82%
Ireland	99.55%	100.00%	11.54%	3.47%	–95.47%	–99.96%	–90.22%	–96.75%
Italy	79.48%	85.75%	61.36%	44.32%	37.49%	–21.08%	–99.14%	–97.39%
Latvia	98.10%	99.69%	63.80%	52.93%	89.28%	74.51%	–85.88%	74.27%
Lithuania	98.02%	92.18%	27.43%	24.72%	–88.31%	–81.04%	86.78%	65.07%
Moldova	99.85%	99.93%	90.14%	86.79%	98.37%	99.56%	–0.12%	58.58%
Netherlands	89.03%	87.86%	65.32%	46.33%	57.47%	–15.22%	–95.62%	71.37%
Poland	93.82%	92.34%	51.15%	51.36%	7.02%	7.10%	92.82%	71.55%
Romania	95.39%	89.04%	62.80%	56.00%	72.53%	25.25%	79.61%	91.97%
Slovakia	96.23%	95.39%	35.63%	38.41%	–72.79%	–60.42%	87.72%	34.22%
Slovenia	97.00%	98.91%	16.81%	16.61%	–91.81%	–97.04%	–44.82%	–98.27%
Spain	84.17%	86.62%	59.25%	54.56%	35.42%	19.55%	–99.87%	–96.00%
Sweden	99.04%	99.62%	12.55%	15.51%	–92.61%	–96.53%	–54.57%	–65.99%
Switzerland	98.66%	98.80%	8.59%	7.08%	–94.67%	–97.07%	–92.02%	–98.44%
United Kingdom	87.36%	96.18%	44.91%	29.90%	–21.12%	–85.60%	–91.00%	–97.27%
CA, SC & Turkey	95.11%	95.05%	55.82%	39.01%	36.50%	–54.28%	–98.53%	33.64%
Azerbaijan	99.32%	93.73%	84.05%	70.22%	95.03%	70.89%	–96.96%	5.59%
Georgia	99.95%	99.05%	69.54%	66.53%	99.87%	97.04%	–99.04%	–93.71%
Kazakhstan	92.56%	92.98%	40.36%	35.89%	–57.74%	–78.44%	–98.24%	–35.00%
Turkey	83.42%	88.29%	58.43%	40.35%	32.92%	–34.75%	–99.11%	60.11%
Uzbekistan	94,51%	89,00%	55,06%	49,29%	32,29%	–3,28%	–92,46%	–99,97%
EA & Pacific	95,18%	98,56%	23,37%	13,62%	–77,24%	–90,37%	–99,98%	–98,74%
ME & N. Africa	99,33%	94,41%	80,25%	58,97%	98,00%	46,67%	–99,10%	35,42%
Iran	89,84%	90,92%	62,58%	43,86%	66,66%	–41,95%	–92,05%	–29,10%
Israel	98,82%	94,31%	71,75%	29,65%	96,65%	–81,68%	–95,00%	64,63%
North America	85,18%	88,34%	39,93%	38,93%	–34,92%	–42,16%	–97,51%	–99,57%
South Asia	83,87%	80,85%	75,65%	36,30%	71,87%	–39,97%	–100,0%	95,30%
World	92,45%	93,81%	44,19%	36,54%	–28,59%	–59,46%	–97,54%	–86,07%

Notes: EA - East Asia, CA - Central Asia, SC - South Caucasus, EU+ - the EU and countries integrated with it (excluding Liechtenstein), ME & N. Africa - Middle East & North Africa; 2) the Europe & CA group contains data on countries for which total volumes of domestic exports or imports in 2021 exceeded USD 200 million; 3) when calculating coefficients of convergence in the space of products, the vector of imports of a certain year was subtracted from the vector of exports of the same year, and the vector of a certain flow of 2021 was subtracted from the vector of the same flow of 2022; 4) relative length of the vector of exports of three products was calculated by dividing its norm by the sum of norms of export and import vectors.

Source: prepared by the authors based on data from the WITS website

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Зовнішня торгівля України 2021–2022 років: векторна модель аналізу наслідків російської агресії

Анотація. Статтю присвячено аналізу впливу повномасштабного російського вторгнення на структуру та динаміку зовнішньої торгівлі України. У статті пропонується векторна модель аналізу вихідних даних. Початок координат у просторі торговельних потоків певної країни може інтерпретуватися двояко – залежно від її геополітичної мети. Для країни, яка прагне збільшити свій вплив на світову економіку, початок координат є станом її нульової світової значущості. З погляду країни, що обрала курс на ізоляцію від світової економіки, початок координат є станом абсолютної автаркії. Норма (довжина) вектора товарообороту (або експорту) характеризуватиме абсолютну величину результату її зусиль. Пропонована модель спирається на геометричні властивості сум та різниць векторів. Відношення цих величин були використані для побудови двох типів коефіцієнтів конвергенції векторів. Коефіцієнти конвергенції, обчислювані за методом суми, було визначено як відношення норми суми векторів до суми їхніх норм. Коефіцієнти конвергенції, обчислювані за методом різниці, було визначено як відношення різниці норм векторів до норми їхньої різниці. Чим більш подібною є структура порівнюваних векторів, тим ближчим до 100% є модуль коефіцієнтів їхньої конвергенції. Аналіз зовнішньої торгівлі України проводився у декількох системах координат: на площині "Експорт – Імпорт", у просторі трьох груп товарів (інвестиційних, споживчих та проміжних), у просторі країн та на площині "Потоки 2021 року – Потоки 2022 року". Порівняльний аналіз скалярної та векторної моделей показав, що пропонована модель є нижньою межею кореляційного зв'язку між частками експорту в українській зовнішній торгівлі 2021 та 2022 рр. Порівняння відносних показників обсягу вітчизняної зовнішньої торгівлі, обчислених на базі двох моделей, показало, що розбіжність між ними невелика і не порушує порядку країн у ранжованому ряді. Коефіцієнти конвергенції торгівлі з європейськими партнерами показали важливість групи проміжних товарів. Коефіцієнти вітчизняної торгівлі з переважною більшістю регіонів та країн перебували у "червоній зоні" – обсяг торгівлі у 2022 р. зменшився, а дворічний обсяг імпорту перевищив дворічний обсяг експорту. При цьому експортно-імпортна структура української торгівлі змінилася мало. Пропонована векторна модель може слугувати інструментом у широкому колі міжнародних досліджень, насамперед геополітичного спрямування

Ключові слова: міжнародні порівняльні дослідження, вектор торговельного потоку, модель DEA, інвестиційні, споживчі та проміжні товари, показники зовнішньої торгівлі, геополітичні фактори зовнішньоекономічної діяльності