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STRUCTURAL SHIFTS AND THE PARTICIPATION OF RUSSIAN INDUSTRIES IN GLOBAL VALUE CHAINS: AN ANALYSIS USING WORLD INPUT–OUTPUT TABLES

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Abstract. Russia actively participates in the international division of labor, global trade, and cross-border value chains. Foreign trade represents a significant share of its gross domestic product. In recent years, the Russian government has been strengthening its public policy to carry out infrastructure and production projects as well as use tax, credit, budgetary, and other policy measures to stimulate economic growth. Hence, there is a growing demand for economic research using mathematical models for managing the economy and industries based on world input-output models with foreign trade blocks highlighted therein. This paper introduces into scientific circulation the world input-output tables created in recent decades, including their brief overview. We propose a model for the Russian economy based on Leontief's Input–Output tables in which each industry's supplies of products to other industries are decomposed into domestic output and import flows. The model is verified using an example of the mining, manufacturing, and transport complexes of Russia. Their output dynamics and structural shifts are estimated for the period 2000–2018 considering the foreign trade component. Special attention is paid to the participation of these complexes in Global Value Chains (GVCs). We present and analyze formulas for determining the participation of industries in GVCs. According to the calculations, Russia's involvement in mining, manufacturing, and transport GVCs is comparable with other countries having large territories, mineral reserves, and transport communications, such as the United States and Australia. Some promising lines to improve the model are described.

Keywords: world input-output tables, industries management, mining, manufacturing, transport, foreign trade, structural shifts, Global Value Chains.

INTRODUCTION

Being not novel, world input-output tables represent an effective and promising economic analysis tool for solving a variety of control and management problems. This tool has been known since the 1980s, the publication of the UN's report *The Future of the World Economy* by a group of experts with famous Russia-born economist W. Leontief. Chapter IV of the report was devoted to the description of the world interregional input–output model [1]. In the report, the blocks of the global model were treated as regions of the world economy. However, this line of economic research has started intensive development in the 21st century, following the appearance of fragmentation theory, global production and value chains, Trade in Value Added, etc. All of them rest on a mathematical framework for describing sustainable development using world input-output tables.

The methodological foundations of modern input–output models as an economic research tool were comprehensively considered in the voluminous UN's handbook [2], containing over 700 pages of text. Not addressing the issues of building world input–output tables, the document nevertheless clearly defined the main vector of their development. Such attention of the world's largest international organization to world input–output tables is not accidental and can be explained as follows.

First, economic globalization brought to the forefront the problems of world economic growth in all its manifestations: patterns, trends, and tendencies; management of international trade and cross-border assets; foreign direct investments; labor migration, etc. Carrying out complex interdisciplinary studies of the connected world required adequate scientific tools. World input–output tables became such an analysis tool.

Second, the rapid growth of labor productivity and productivity in the late 20th–early 21st centuries was largely due to increasing cross-border production cooperation as well as expanding the foreign supplies of products and capital investments. These processes also brought to the forefront the task of developing adequate methodological, statistical, and mathematical tools for studying global processes in the field of cross-border production and management.

Third, computerization and digitalization enabled researchers to create complex, multi-parametric, and high-dimensional models of economic development at their workplaces in real time and include intersectoral cross-border linkages in such models, thereby obtaining a more complete, structured, and disaggregate (at the levels of sectors and industries) picture of the development of the world economy. Powerful computers and appropriate software created conditions for processing large arrays of statistical and other information, including world input–output tables of high dimensions.

1. MODELS AND DATABASES: A SURVEY

1.1. Theoretical Foundations

In recent years, input–output models, particularly their compilation and calculations, have become an important subject in the theory and applied research of control and management in socio-economic systems. Works in this area activated after the global financial and economic crisis of 2008–2009: despite numerous studies of the world economy, carried out using complex, multi-parameter, stochastic, and game-theoretic forecasting models, no one was able to predict its onset.

Another factor contributing to the widespread use of input–output models in control and management was the concepts of *Global Value Chains* (GVCs) and *Trade in Value Added* (TiVA), which emerged around the same time. International organizations (the UN, UNCTAD, and WTO) expressed interest in these concepts, which gave an additional impetus to the development of world input–output tables. In particular, in 2016, the UN issued the *Guide to Measuring Global Production*, where both concepts played key roles [3].

The main methodological problem tackled by researchers since the early 2000s was to decompose mathematically country’s gross exports into various value-added components by source. Many schools of economics were engaged in the theoretical studies of this problem. In the 2010s, a solution was proposed by a group of scientists and experts led by R. Koopman, Chief Economist and Director of Economic Research of the United States International Trade Commission (USITC) [4]. The corresponding formulas for export components in value-added terms were used to create the TiVA Database [5] of OECD and WTO.

Among the publications of recent years, we emphasize the working paper by a group of scientists led by R. Baldwin, a well-known professor of international economics at the Geneva Graduate Institute [6]. The paper considered tools for assessing the impact of external shocks on global value chains and presented a systematic approach to developing appropriate indicators. In particular, on the example of three countries (USA, China, and Mexico), the tracking mechanism of a three-linkage supply chain was analyzed in detail: the imports of intermediate products (the first linkage), processing (the second linkage), and exports to the third country (the third linkage). A mathematical apparatus using input-output tables was described as well. A formula and algorithm for decomposing gross exports into value-added components were proposed by other researchers [7].

The EU’s technical report enables to fully decompose the factor content of bilateral trade measured at the border and account for the specific of the different countries and industries participating in GVCs [8]. It provided and justified new formulas for calculating the ratio of value added and exports in multiregional input-output tables.

1.2. Applied Research

Since Leontief’s times, a major line of applied research based on input–output models has been the calculation of structural changes in the economy and the assessment of the impact of production factors on economic growth. Currently, several international peer-reviewed journals are devoted to the analysis of structural shifts. In this context, we mention *Structural Change and Economic Dynamics*, a Scopus-indexed journal issued by Elsevier (the Netherlands). It pays much attention to the development and application of the world input-output tables in economic analysis. For example, structural shifts between large groups of countries in the world economy were studied in the paper [9]. As was demonstrated by the authors, participation in global value chains can facilitate the process of structural transformations in developing economies.

In 2011, *the Pan-Pacific Association of Input-Output Studies* (PAPAIOS) established *The Journal of Economic Structures*, an interdisciplinary periodical indexed by Scopus. The publication [10] in this journal analyzed statistical data series on the economic growth of several OECD countries for 1995–2011. The contribution of final demand components was determined using the input-output model.

An interesting applied study for the automotive industry was carried out by M. Timmer et al., the developers of the World Input–Output Database (the University of Groningen, the Netherlands) [11]. Using input-output tables for the world economy, they considered the dynamics of shifts in the geographical distribution of value added in the global automotive industry for 1995–2011. According to the conclusions, there is a growing international fragmentation of production processes in the industry, within the regions and also between them.

In recent years, due to the increasing frequency of man-made and natural disasters, more and more publications have been focused on assessing the impact of various force majeure, from earthquakes and floods to the COVID-19 pandemic, on the economy and individual industries. For example, a global input–output table (35 industries, 29 endogenous and 59 exogenous countries) was built and used to analyze the transfer mechanism of shocks from the fall in demand for finished goods [12]. Also, the cited authors developed special indices to measure the degree of reduction in value added and the output of intermediate products.

The economic effects of the 2016 earthquake in Kumamoto Prefecture, Japan, were studied in the paper [13]. Using an interregional input-output table, the authors modeled the negative effects on consumer spending and value added in different regions of the country. In addition, the positive impact of a sharp increase in aggregate government and household expenditures on reconstruction and construction was estimated. The net increase in value added was estimated considering intersectoral linkages. According to the conclusions, despite the earthquake's direct economic damage to Kumamoto Prefecture, the economic response activities exceeded the damage, ensuring the rapid economic recovery of the region.

The study [14] was devoted to economic losses from cyber-attacks in Japan using an input-output model with a production function. Within this model, the objective function is the amount of damage and the effectiveness of various government measures to reduce and prevent damage. The initial numerical information is the working time losses due to cyber-incidents. These data were applied to the input–output table to calculate indirect effects. As a result, direct and indirect damages were estimated for all industries of Japan's economy in terms of working time losses.

The most popular topic in recent years has been the COVID-19 pandemic. A considerable amount of literature has been devoted to assessing its impact using input–output tables as a research tool with the fullest consideration of direct and indirect effects. For example, the economic sectors with the potentially highest vulnerability to the COVID-19 pandemic were identified using graph theory and input-output tables [15]. The analysis was carried out for the eight largest countries, including Russia. As was discovered, in all countries, the priority sectors for the governments to support were manufacturing, real estate, and wholesale trade.

1.3. Databases

Over the past decades, several projects have been implemented in the world to create global models with databases containing input-output tables. They are developed and maintained by private organizations as well as on the orders of different authorities.

In this area, one of the pioneering world-class developments is the Global Trade Analysis Project (GTAP) database.[1] Existing since 1992, it was created by a consortium of US universities and private and international organizations in order to provide users with various structured statistical and calculated numerical information on economic indicators. It is hosted by Purdue University (USA). The GTAP is based on a multiregion, multisector computable general equilibrium model with perfect competition and constant returns to scale. Its core is a database of world bilateral trade, production, consumption, and intermediate uses of goods and services ("input–output"). GTAP ver. 11 contains data for years 2004, 2007, 2011, 2014, and 2017 by 65 industries in 141 countries (including Russia). It can be structured by 19 regions of the world, i.e., is a multi-region model.

In 2009, the EU decided to support the development project of its own database of input–output models, the World Input-Output Database (WIOD). By the EU's order, this work was carried out for several years by a consortium of European universities and research centers. The database is maintained by the head organization of the consortium, i.e., the University of Groningen.[2] The current version of 2016 contains 15 annual world input–output tables for 2000–2014, covering 43 countries (27 EU countries + 16 non-EU countries, including Russia) + "the rest of the world" and 56 industries.

[1] URL: https://www.gtap.agecon.purdue.edu/. (Accessed February 19, 2024.)

[2] URL: https://www.rug.nl/ggdc/valuechain/wiod/?lang=en. (Accessed February 19, 2024.)

The Multiregional Input-Output Tables[3] (MRIO) database is an extension of WIOD with the supplementary tables of Asia-Pacific countries. It includes 19 countries in addition to the 6 Asian countries present in WIOD. Since 2014, MRIO compilation has been led and funded by the Asian Development Bank. The database contains national input-output tables for 26 Asia-Pacific countries for 2000–2020.

In this paper, we use information from the Inter-Country Input-Output[4] (ICIO) database, the version of 2021, of the Organization for Economic Cooperation and Development (OECD). ICIO tables were compiled for 1995–2018 for 67 countries (including Russia) with decomposition by 45 industries according to the International Standard Industry Classification (ISIC) of all economic activities, the version of 2009.

2. THE MODEL

2.1. World Input–Output Tables

Our interpretation of the mathematical model of world input–output tables is presented in Table 1.

This model has the following notations:

a_{ij}^{mn} is the value of intermediate products manufactured by industry i of country m and consumed by industry j of country n;

y_{ik}^{mn} is the value of products manufactured by industry i of country m and used for final consumption $k = 1,..., K$ of country n. As a rule, final consumption includes three groups of costs: the final use of goods

Table 1

World Input–Output Tables

Costs		Output										
		Intermediate products					Final product					Gross output
		1_1	...	n_j	...	N_J	1_1	...	n_k	...	N_K	
Country 1	1_1	a_{11}^{11}	...	a_{1j}^{1n}	...	a_{1J}^{1N}	y_{11}^{11}	...	y_{1k}^{1n}	...	y_{1K}^{1N}	x_1^1
	2_1	a_{21}^{11}	...	a_{2j}^{1n}	...	a_{2J}^{1N}	y_{21}^{11}	...	y_{2k}^{1n}	...	y_{2K}^{1N}	x_2^1
	...	...	...	...	...	...	...	...	...	...	...	...
	I_1	a_{I1}^{11}	...	a_{Ij}^{1n}	...	a_{IJ}^{1N}	y_{I1}^{11}	...	y_{Ik}^{1n}	...	y_{IK}^{1N}	x_I^1
Country 2	1_2	a_{11}^{21}	...	a_{1j}^{2n}	...	a_{1J}^{2N}	y_{11}^{21}	...	y_{1k}^{2n}	...	y_{1K}^{2N}	x_1^2
	2_2	a_{21}^{21}	...	a_{2j}^{2n}	...	a_{2J}^{2N}	y_{21}^{21}	...	y_{2k}^{2n}	...	y_{2K}^{2N}	x_2^2
	...	...	...	...	...	...	...	...	...	...	...	...
	I_2	a_{I1}^{21}	...	a_{Ij}^{2n}	...	a_{IJ}^{2N}	y_{I1}^{21}	...	y_{Ik}^{2n}	...	y_{IK}^{2N}	x_I^2
	...	...	...	...	...	...	-	-	-	-	-	-
Country m	1_m	a_{11}^{m1}	...	a_{1j}^{mn}	...	a_{1J}^{mN}	y_{11}^{m1}	...	y_{1k}^{mn}	...	y_{1K}^{mN}	x_1^m
	2_m	a_{21}^{m1}	...	a_{2j}^{mn}	...	a_{2J}^{mN}	y_{21}^{m1}	...	y_{2k}^{mn}	...	y_{2K}^{mN}	x_2^m
	...	...	...	...	...	...	...	...	...	...	...	...
	I_m	a_{I1}^{m1}	...	a_{Ij}^{mn}	...	a_{IJ}^{mN}	y_{I1}^{m1}	...	y_{Ik}^{mn}	...	y_{IK}^{mN}	x_I^m
	...	...	...	...	...	...						
Country M	1_M	a_{11}^{M1}	...	a_{1j}^{Mn}	...	a_{1J}^{MN}	y_{11}^{M1}	...	y_{1k}^{Mn}	...	y_{1K}^{MN}	x_1^M
	2_M	a_{21}^{M1}	...	a_{2j}^{Mn}	...	a_{2J}^{MN}	y_{21}^{M1}	...	y_{2k}^{Mn}	...	y_{2K}^{MN}	x_2^M
	...	...	...	...	...	...	...	...	...	...	...	...
	I_M	a_{I1}^{M1}	...	a_{Ij}^{Mn}	...	a_{IJ}^{MN}	y_{I1}^{M1}	...	y_{Ik}^{Mn}	...	y_{IK}^{MN}	x_I^M
Added value		v_1^1	...	v_j^n	...	v_J^N	-		-		-	-
Gross output		x_1^1	...	x_j^n	...	x_J^N	-		-		-	-

[3] URL: https://www.adb.org/what-we-do/data/regional-input-output-tables. (Accessed February 19, 2024.)

[4] URL: https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm. (Accessed February 19, 2024.)

and services for household, government, and non-profit institutions serving households; capital formation, changes in inventories, and the net acquisition of valuables; net exports (exports minus imports);

x_i^m is the gross output produced by industry i of country m;

v_j^n is the value added in industry j of country n. It can be represented as the sum of several components (categories) such as wages, gross profit, gross income, taxes and subsidies (–), fixed assets;

$i, j \in \{1, 2,..., I\}$, i and j indicate industries in the rows and columns of the world input–output table, respectively, where I is the number of industries and $J = I$;

$n, m \in \{1, 2,..., N\}$, n and m indicate countries in the rows and columns of the world input–output table, respectively, where N is the number of countries and $M = N$;

$k \in \{1, 2,..., K\}$, k indicates the final consumption component, and K is the number of final consumption components in the world input–output table.

The gross output x_i^m produced by industry i of country m by rows can be represented as the sum of intermediate and final consumption:

$$x_i^m = \sum_{n=1}^{M}\sum_{j=1}^{I} a_{ij}^{mn} + \sum_{n=1}^{M}\sum_{k=1}^{K} y_{ik}^{mn} . \quad (1)$$

By columns, it can be represented as the sum of intermediate consumption and value added:

$$x_j^n = \sum_{m=1}^{M}\sum_{i=1}^{I} a_{ij}^{mn} + v_j^n . \quad (2)$$

Let us transform the initial equations and introduce new notations.

We construct the new gross output vector $\hat{\mathbf{X}}$ by sequentially arranging the gross outputs x_i^m by countries $m = 1, 2,..., M$:

$$\hat{\mathbf{X}} = \{x_1^1, x_2^1, \ldots, x_I^1, x_1^2, x_2^2, \ldots, x_I^2, ..., x_1^M, x_2^M, \ldots, x_I^M\}.$$

The vector $\hat{\mathbf{X}}$ contains $(I \times M)$ components. Denoting this number by R and the components of the vector $\hat{\mathbf{X}}$ by $\hat{x}_r$, we write the vector $\hat{\mathbf{X}}$ as

$$\hat{\mathbf{X}} = \{\hat{x}_r\}_{r=1,\ldots,R}.$$

By analogy, we construct the world economy's final consumption vector $\hat{\mathbf{Y}} = \{\hat{y}_r\}_{r=1,\ldots,R}$, where $\hat{y}_r$ is the final consumption indicators for all industries sequentially arranged country-by-country.

With all rows and columns numbered from 1 to R, the intermediate flows matrix $\{a_{ij}^{mn}\}_{i,j=1,2,\ldots,I}^{m,n=1,2,\ldots,M}$ can be represented as

$$\hat{\mathbf{A}} = \{\hat{a}_{rs}\}_{r,s=1,\ldots,R}.$$

Next, we calculate the direct input coefficients c_{rs} (technological coefficients) of the world input–output table: $c_{rs} = \hat{a}_{rs} / \hat{x}_s$, where r and s are the row and column, respectively.

Then the direct input coefficient matrix of the world input–output table takes the form

$$\mathbf{C} = \{c_{rs}\}_{r,s=1,2,\ldots,R},$$

and the input–output model equation is written as

$$\hat{\mathbf{X}} = \mathbf{C}\hat{\mathbf{X}} + \hat{\mathbf{Y}}$$

or

$$\hat{\mathbf{X}} = (\mathbf{E} - \mathbf{C})^{-1}\hat{\mathbf{Y}} \quad (3)$$

with the following notations: $\hat{\mathbf{X}}$ is the gross output vector $\{\hat{x}_r\}_{r=1,\ldots,R}$; $\hat{\mathbf{Y}}$ is the final consumption vector $\{\hat{y}_r\}_{r=1,\ldots,R}$; $\mathbf{C}$ is the direct input coefficient matrix $\{c_{rs}\}_{r,s=1,2,\ldots,R}$; finally, $\mathbf{E}$ is an identity matrix of dimensions $R \times R$. (The elements of the principal diagonal are one, and all other elements are zero.)

2.2. ICIO Input–Output Tables

Information from the ICIO database, the version of 2021 (see footnote 4 on p. 26), was used to carry out calculations by formula (3). Our model (1)–(3) is the world input–output table with the following parameters: i, j = 1, ..., 45; I, J = 45 (the number of industries); m, n = 1, ..., 67; M, N = 67 (the number of countries); r = 1, ..., 3015; R = 3015 (the number of rows and columns).

The final consumption vector $\hat{\mathbf{Y}}$ is presented in ICIO in terms of K = 6 components (k = 1,..., 6): household consumption; expenditures of non-profit institutions serving households; direct purchases by non-residents; government final consumption; capital formation and changes in inventories [5, *p. 10*].

In ICIO, each country's matrix of intermediate products $\mathbf{A} = \{a_{ij}\}$ is decomposed into two matrices as follows:

$$\mathbf{A} = \mathbf{AD} + \mathbf{IM}, \quad (4)$$

where $\mathbf{AD} = \{a_{ij}^d\}_{i,j=1,\ldots,I}$ is the matrix of *domestic intermediate inputs* and $\mathbf{IM} = \{im_{ij}\}_{i,j=1,\ldots,I}$ is the matrix of *intermediate imports*).

The final consumption components are similarly decomposed into domestic products and direct imports.

2.3. Assessing the Participation of Russian Industries in Cross-border Value Chains

The matrix of intermediate imports is available in the ICIO database for the Russian economy. Therefore, it is possible to assess the involvement of Russian industries in global value chains (GVCs). For this purpose, we calculate the volume of intermediate imports included in exports from the ICIO tables (see footnote 4 on p. 26) by the formula

$$\mathbf{ImCEx} = \mathbf{CIM}(\mathbf{E} - \mathbf{CAD})^{-1}\,\mathbf{Ex}, \qquad (5)$$

where:

$\mathbf{ImCEx} = \{imce_j\}_{j=1,\ldots,I}$ is the vector of intermediate imports that are included in exports for each industry (the imports content of exports);

$\mathbf{CIM} = \{im_{ij} / x_j\}_{ij=1,\ldots,I}$ is the matrix of direct input coefficients for the imports of industry *i* when obtaining the latter in industry *j*, derived from the matrix **IM** (4);

$\mathbf{CAD} = \{a_{ij}^d / x_j\}_{ij=1,\ldots,I}$ is the matrix of direct input coefficients for domestic products (i.e., excluding imports) when obtaining products in industry *j*, derived from the matrix **AD** (4);

finally, $\mathbf{Ex} = \{ex_i\}_{i=1,\ldots,I}$ is the vector of exports by industries.

Economically, the *j*th component $imce_j$ of the vector $\mathbf{ImCEx}$ means the products imported by all industries for intermediate consumption that are included in the exports of industry *j*. Indeed, the matrix of import direct costs, $\mathbf{CIM}$, is multiplied by the matrix of full cost coefficients for domestic products, $(\mathbf{E} - \mathbf{CAD})^{-1}$, which is (in turn) multiplied by the vector of exports.

These indicators have the following economic interpretation:

- The *I*–dimensional vector $(\mathbf{E} - \mathbf{CAD})^{-1}\mathbf{Ex}$, where *I* is the number of industries (see the variables in Table 1) shows how much domestic gross output is needed to obtain the volume of exports **Ex** (an analog of the final product supplied abroad);
- The matrix $\mathbf{CIM}$ of dimensions ($I \times I$) consists of intermediate imports per unit of gross output of each industry. Multiplying this matrix by the vector $(\mathbf{E} - \mathbf{CAD})^{-1}\mathbf{Ex}$ gives the vector of imports content of exports (by industry $i = 1,\ldots, I$).

The imports content of exports (the vector $\mathbf{ImCEx}$), or the import component of exports, is the contribution of imports to the output of exported goods and services. It represents an indicator of the industry's involvement in global value chains through imports. Thus, a chain contains at least three countries, namely, the manufacturer of imported products, the country where the imports are processed, and the consumer of the exported products. Also, this indicator reflects the vertical specialization of the country and its industries in the global economy [16, *p. 6*].

2.4. Equations for Russia's Industrial Complexes

The mining, manufacturing, and transport complexes in ICIO, particularly for Russia, are presented in terms of the following sectors (with the numbers according to the original tables):

3. Mining and quarrying, energy producing products;
4. Mining and quarrying, non-energy producing products;
5. Mining support service activities;

6–22. Manufacturing, incl.:

10. Coke and refined petroleum products;
15. Basic metals;

20, 21. Motor vehicles, trailers and semi-trailers; Other transport equipment;

22. Manufacturing nec[5]; repair and installation of machinery and equipment;
35. Land transport and transport via pipelines;
36. Water transport;
37. Air transport;
38. Warehousing and support activities for transportation.

In the model, see formula (1), the gross output of Russia's complexes is calculated by

$$x_d^{\mathrm{RF}} = \sum_{s=3}^{5}\left(\sum_{j=1}^{45} a_{sj}^{\mathrm{RF}} + \sum_{k=1}^{6} y_{sk}^{\mathrm{RF}}\right), \qquad (6)$$

$$x_o^{\mathrm{RF}} = \sum_{s=6}^{22}\left(\sum_{j=1}^{45} a_{sj}^{\mathrm{RF}} + \sum_{k=1}^{6} y_{sk}^{\mathrm{RF}}\right), \qquad (7)$$

$$x_t^{\mathrm{RF}} = \sum_{s=35}^{38}\left(\sum_{j=1}^{45} a_{sj}^{\mathrm{RF}} + \sum_{k=1}^{6} y_{sk}^{\mathrm{RF}}\right), \qquad (8)$$

where x_d^{RF}, x_o^{RF}, and x_t^{RF} are the gross outputs of the Russian mining, manufacturing, and transport com-

[5] Not elsewhere classified.

plexes, respectively; a_{sj}^{RF} is the intermediate products from industry s to industry j of the Russian economy, including imports, where s = 6,..., 22 and j = 1, 2,..., 45; y_{sk}^{RF} is the final consumption of component k of the products of industry s in Russia, including imports, where k = 1,..., 6.

3. MODEL CALCULATIONS AND ECONOMIC ANALYSIS

Model (1)–(8) was tested on the example of the mining, manufacturing, and transport complexes. This choice is explained by their importance for the Russian economy and the high degree of their involvement in cross-border value chains. We calculated the indicators of structural shifts in these complexes and their involvement in cross-border value chains as well as compared the results with other countries.

According to the calculations, during 2000–2018, the mining and transport complexes were the drivers of Russia's economic development. The growth of their output outpaced other macroeconomic indicators, in particular, gross domestic product (GDP) and gross output in the country. While Russia's GDP and gross output increased 6-fold between 2000 and 2018, the outputs of the mining and transport complexes demonstrated growth rates of 7.2 and 6.4 times, respectively. (Hereinafter, all values are in current USD.) The share of the manufacturing complex in the gross output of the Russian economy decreased from 27.5% to 26.0%. In value-added terms, mining and quarrying increased from \$39.1 billion in 2000 to \$280.4 billion in 2018. The output of transport sectors rose from \$34 billion to \$217 billion over the same period.

A powerful internal driver of Russia's development was scientific and technological progress, which dramatically increased efficiency and optimized the management of product flows, warehousing, and support activities. Due to their outpaced growth, there were significant structural shifts within the complexes.

In mining and transportation, support activities, including warehousing, management, and services, as well as mineral exploration, became more important. In the mining complex, the share of energy resources decreased from 85.8% in 2000 to 78.8% in 2018, while the share of support service activities almost tripled over the same period, from 3.7% to 10.1% (see Fig. 1).

In the manufacturing complex, the shifts in many respects followed the mining trends. In the structure of the manufacturing complex, the share of coke and refined petroleum products increased most significantly (Fig. 2). Also, the share of motor vehicles, trailers and semi-trailers in the manufacturing complex slightly grew, but the relative level of basic metals decreased.

In transportation, structural shifts were even more considerable: the share of logistics, management, warehousing, and other support activities in gross output increased 2.4 times from 13.1% in 2000 to 31.6% in 2018 (see Fig. 3).

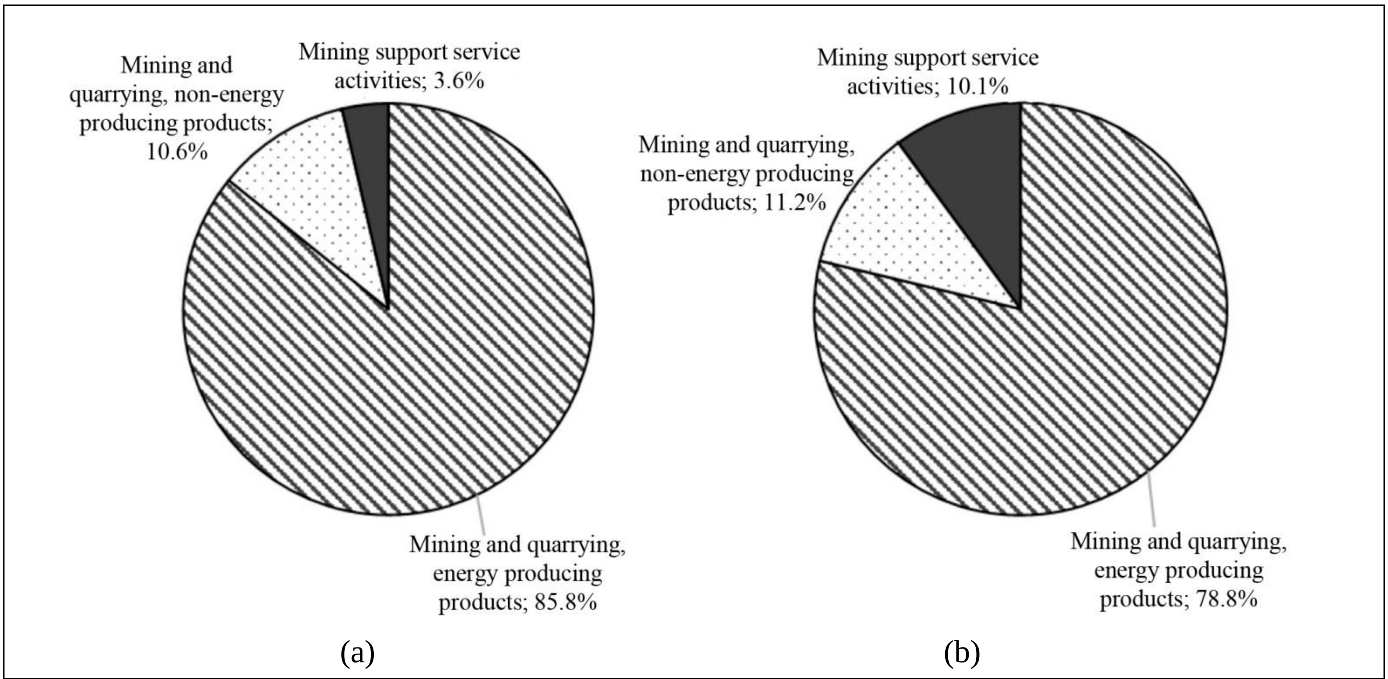

Fig. 1. The gross output structure of Russia's mining complex: (a) year 2000 and (b) year 2018.

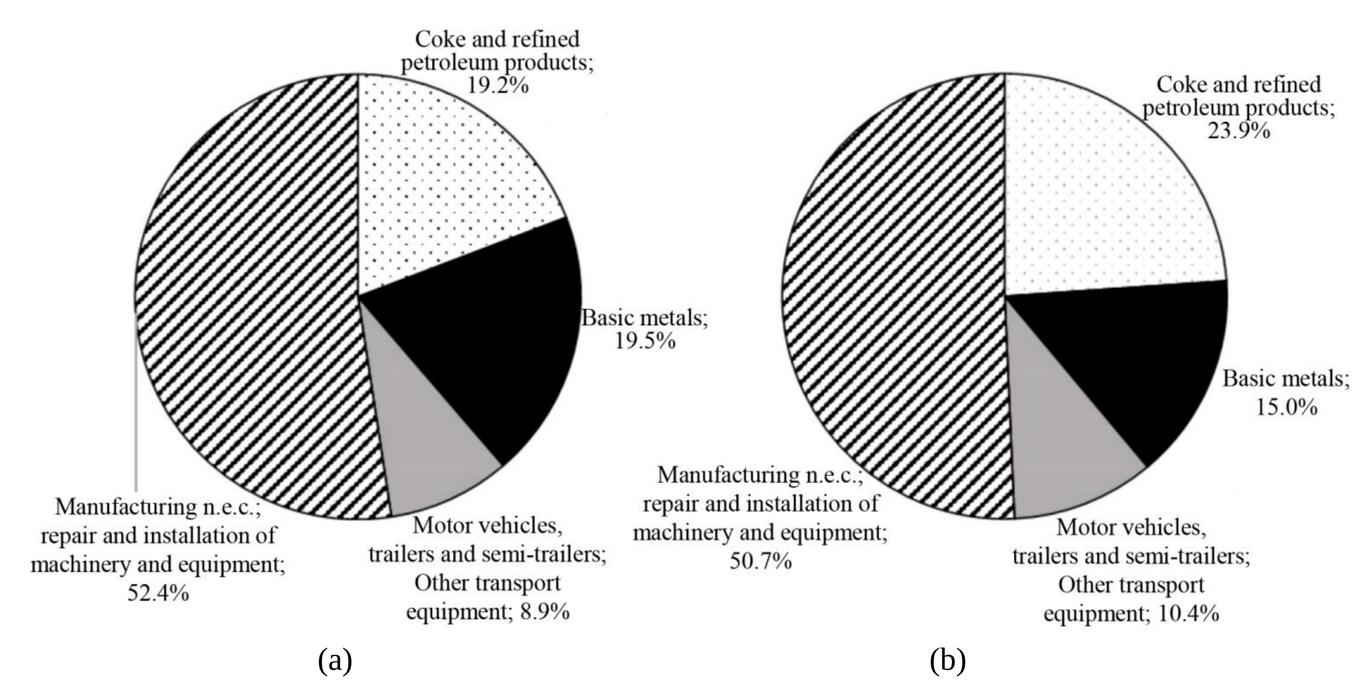

Fig. 2. The gross output structure of Russia's manufacturing complex: (a) year 2000 and (b) year 2018.

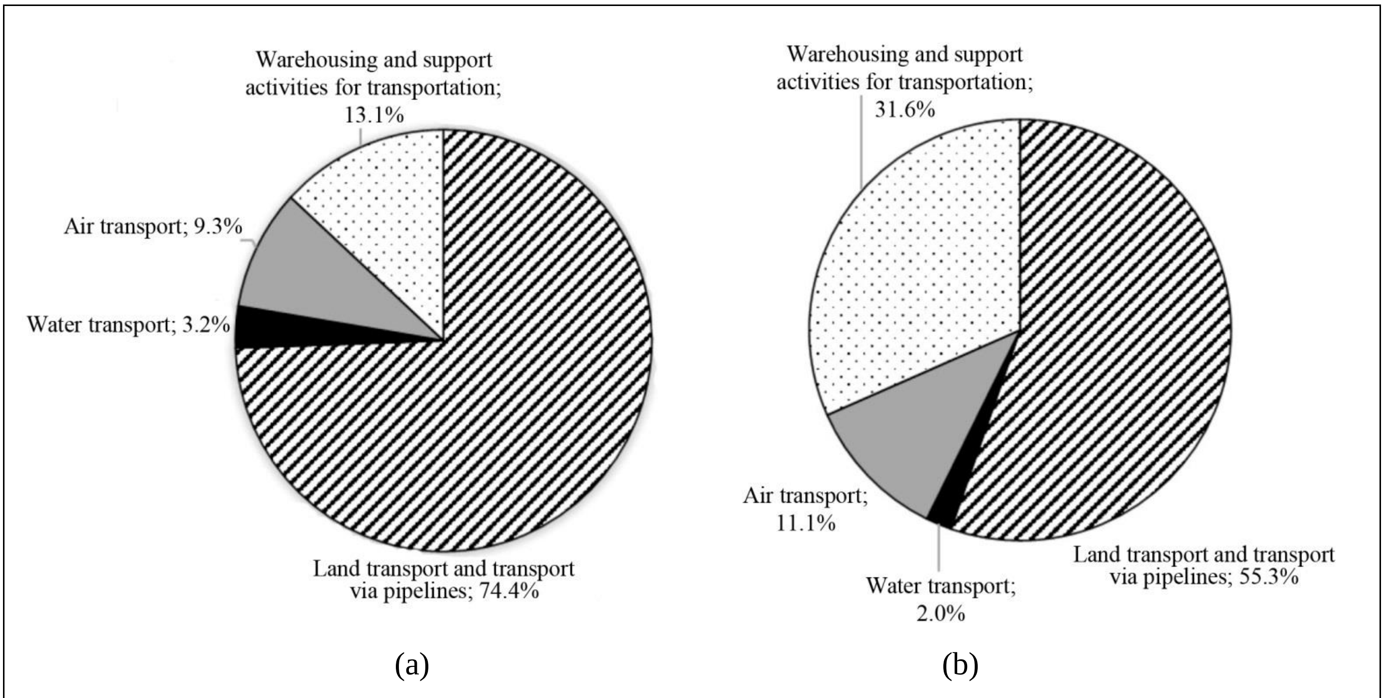

Fig. 3. The gross output structure of Russia's transport complex: (a) year 2000 and (b) year 2018.

The share of air transport also increased due to the active involvement of the economy in global value chains and the rapid development of foreign tourism.

No significant shifts were observed in macrostructural "industry–services" indicators. The share of services remained almost unchanged throughout the entire period at a level of 60.2–60.8% in 2000–2018.

In all three complexes, imports were growing at a particularly high rate, and their involvement in global value chains was taking place. The intra-sectoral consumption of imported products in mining sectors increased 16 times, from $50 million in 2000 to almost $800 million in 2018. This figure much exceeds the overall increase in imports across the Russian economy (5.5 times). At the same time, considering the intra-sectoral, cross-sectoral, and final consumption, imports in the mining complex increased only 4.5 times, from $693 million in 2000 to $3.1 billion in 2018.

In Russia's transport complex, imports increased 6.5 times, from $4.8 billion in 2000 to $31.5 billion in 2018. As a result, its share in total imports grew from 7.5% to 9.0%. This high import dependence negatively affected the transport complex during the COVID-19 pandemic and the subsequent economic stagnation.

According to the calculations by formula (5), Russia's involvement in cross-border value chains in the mining, manufacturing, and transport complexes is comparable with other countries having significant territories, volumes of mining and quarrying, and extensive transportation networks (USA and Australia); see Table 2.

In some sectors, Russia is ahead of these countries, being behind in others. But all three countries—Russia, USA, and Australia—are significantly behind China in terms of cross-border production cooperation. This fact is explained by China's higher degree of integration into the global economy as the world's factory and the main exporter of products.

CONCLUSIONS

Over the last decade, world input–output tables have been actively created by international organizations. In the conditions of globalization, the cross-border division of labor, and the intensification of foreign trade, they are in demand by governments and researchers as an economic analysis tool for developing and assessing the effectiveness of economic and political decisions. They can be used to control socio-economic development and production, carry out simulations, and estimate the sensitivity of economic systems, industries, and complexes in order to develop optimal management decisions by the states and large companies operating in global markets.

In this paper, a model has been proposed, and model-based calculations have been carried out to assess the place and role of Russia's mining, manufacturing, and transport complexes. According to the calculations, it is important to manage these complexes in order to improve the efficiency of the Russian economy. The flows of imported products as part of intermediate and final consumption have been separated in input–output tables, and the following conclusion has been drawn accordingly: with the gradual intensification of the involvement of Russia's mining sectors and transport in international cooperation, their role as a driver of the country's economy was growing. The development of both national economic complexes for almost 20 years (2000–2018) was proceeding at a faster pace.

The calculations demonstrated that there were major structural shifts in Russia's mining and transport complexes in 2000–2018, mainly due to scientific and technological progress. Among the sectors of both complexes, the highest growth rates were observed for management expenditures, warehousing, and support activities.

Based on this study, it can be generally concluded that Russia's mining and transport complexes in the period before the COVID-19 pandemic had sustainable and generally optimal strategies for development and involvement in global value chains.

The model proposed in this paper can be further improved and expanded in the following promising areas of application:

– management of import substitution in Russia at the sectoral level (by introducing a new block of import restrictions and an efficiency criterion in the model, as well as an algorithm for finding an optimal strategy under such restrictions);

Table 2

The share of imports in exports: Russia and other countries in 2018, in %

Sectors	Russia	USA	Australia	China
Mining and quarrying, energy producing products	3.9	11.4	7.1	12.5
Mining and quarrying, non-energy producing products	7.0	9.0	9.8	15.7
Mining support service activities	12.5	6.8	8.5	16.3
Coke and refined petroleum products	5.9	28.4	24.2	39.6
Basic metals	11.8	20.9	17.3	17.8
Motor vehicles, trailers and semi-trailers; Other transport equipment	34.8	27.2	30.2	14.3
Land transport and transport via pipelines	7.7	5.9	14.0	9.6
Water transport	12.4	7.5	10.6	20.1
Air transport	14.3	5.2	20.6	16.2
Warehousing and support activities for transportation	10.5	5.9	5.9	14.5
The overall economy	8.7	10.1	10.8	17.1

– management of greenhouse gas emissions at the level of sectors and productions (by introducing an environmental block into the model);

– management of taxes and profit (by introducing a separate component in value added and using, e.g., the methodology proposed in [17]).

The model can include pricing and dynamics and be used to manage, forecast, and plan the entire economy and separate sectors. In addition, it can be used as a basis for solving different classes of simulation and optimization problems of managing the Russian economy under sanctions and other restrictions, in particular, within the theory of management of multi-resource self-developing systems, optimization of the technological core of an economy with the productivity criterion, optimal planning, and other approaches described in [18–20].

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