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Analysis of the international trade networks of COVID-19 medical products

Marcell T. Kurbucz[1,2*], András Sugár[2] and Tibor Keresztély[2]

*Correspondence:
kurbucz.marcell@wigner.hu

[1] Department of Computational Sciences, Wigner Research Centre for Physics, 29-33 Konkoly-Thege Miklós Street, Budapest 1121, Hungary
[2] Institute of Data Analytics and Information Systems, Corvinus University of Budapest, 8 Fővám Square, Budapest 1093, Hungary

Abstract

This research aimed to gain a deeper understanding of how and for what reasons the world trade networks of medical products were reorganized during the novel coronavirus (COVID-19) pandemic. To do this, first, the trade data of eight COVID-19-related product categories (such as medical test kits and protective garments) were collected for the years 2019 and 2020. Then it was examined which countries' exports and imports changed the most between the studied time period in each product category. In addition, gravity models containing additional economic, geographic, and COVID-19-related variables were used to analyze the impact of the pandemic on the investigated trade networks. Based on the results, China achieved the highest cumulative export growth, surpassing the second-highest value by approximately 14.66. Hungary, with a population of only 9.7 million, stood out as a major importer of ventilators. Additionally, a higher incidence of COVID-19 among importers typically led to reduced traded values, while European Union membership and innovation capacity had the opposite effect.

Keywords: COVID-19, International trade, Medical products, Social network analysis, Multilevel network, Gravity model

Introduction

The sudden appearance and rapid spread of the disease caused by the novel coronavirus (COVID-19) affected a world that was mostly unprepared (Lippi et al. 2020). Although the World Health Organization (WHO) declared COVID-19 as a pandemic on March 11, 2020, in the first months of that year, the export of related medical products was already restricted or completely banned by the governments of more than 50 countries worldwide (Bown 2020; Alert 2020). According to a World Trade Organization (WTO) report (Organization) 2020), the number of these countries rose to 80 as of April 23, 2020. Even if these restrictions were typically short-lived and related to a narrow range of goods, they could have had serious economic and geopolitical consequences (Campbell and Doshi 2020; Javorcik 2020; Weinhardt and Ten Brink 2020; Grassia et al. 2022).

Since the outbreak of the COVID-19 pandemic, numerous studies have investigated the export of medical products. Among these, Fuchs et al. (2020) and Telias and Urdinez (2021) examined the Chinese export and donation of these products during the pandemic. Hayakawa and Mukunoki (2021) analyzed the impact of COVID-19 on world trade. Hayakawa and Imai (2022) examined the trade of medical products, including medicines, personal protective equipment, and health and medical equipment, and Grassia et al. (2022) tried to estimate the effects of restrictions on the export of these products. As Grassia et al. (2022) emphasized, this area of research not only helps to understand the causes and effects of restrictions on free trade but also sheds light on how individual countries react to a global crisis caused by the pandemic.

Research in this field often relies on the gravity equation of trade (Kabir et al. 2017), an econometric model that aims to explain bilateral trade flows between countries by taking into account factors such as economic size, distance, and other relevant variables. Some of these empirical works focus on a specific country, such as China (Fuchs et al. 2020; Liu et al. 2022; Pu et al. 2023) or Malaysia (Zainuddin et al. 2021). Others explore multiple economies (Jindřichovská and Uğurlu 2021) or, similar to our paper, the global economy (Hayakawa and Mukunoki 2021).

The aim of this research was to gain a deeper understanding of how and for what reasons the world trade networks of medical products were reorganized during the COVID-19 pandemic. To do this, first, the trade data of eight COVID-19-related product categories (such as medical test kits and protective garments) were collected for the years 2019 and 2020. Then it was examined which countries' exports and imports changed the most between the studied time period in each product category. Finally, gravity models containing additional economic, geographic, and COVID-19-related variables were used to analyze the impact of the pandemic on the investigated trade networks.

Based on the results, China exhibited the highest cumulative export growth, mainly due to a significant increase in protective garment exports, surpassing the second-highest value by a factor of approximately 14.66. Despite its small population of 9.7 million, Hungary stood out as one of the main importers of ventilators. Additionally, gravity models showed that a higher incidence of COVID-19 among importers typically led to reduced traded values, while European Union (EU) membership and innovation capacity had the opposite effect. The main implications of the results can be summarized as follows:

- The results emphasize China's pivotal role in global supply chains for medical products, specifically regarding protective garments, which have emerged as one of the most crucial product categories in the fight against the pandemic.
- The import patterns of medical products were less concentrated, showing no clear asymmetry among the top importing countries. However, Hungary, despite its small population, stood out as a major importer by purchasing a substantial number of ventilators from China.
- Regional trade agreements (RTAs) and EU membership of exporter countries positively influenced the traded value, while they had a negative effect on importers. This suggests that trade integration within regional blocs played a significant role in shaping trade dynamics during the pandemic.
- The number of COVID-19 cases in exporting countries had a significant impact on the trade of protective garments, indicating that countries heavily affected by

the pandemic experienced significant trade restrictions for this specific product category.

- Future research should consider focusing on the ego networks of key exporters and importers could provide valuable insights into the broader effects of the pandemic on various economic sectors. In addition, long-term investigation and comparison of trade networks could help elucidate the lasting effects of the COVID-19 pandemic and reveal potential shifts and consolidations in global trade relations in the post-pandemic era.

The rest of this paper is organized as follows. The "Data and methodology" section introduces the data employed in this study, as well as the applied methodology and software. The "Results and discussion" section presents and discusses the results of the social network- and gravity model-based analysis. Finally, the "Conclusions and future work" section provides a summary and conclusions.

Data and methodology

Data sources

In this paper, three databases are employed. The first is the source of international trade data related to medical products, while the economic, and geographic variables, as well as the COVID-19-related health data, are obtained from another two data sources.

International trade database

Information related to the trading data of COVID-19-related medical products is obtained from the database called BACI (Gaulier and Zignago 2010).[1] BACI provides yearly data on bilateral trade flows for 200 countries at the product level. Of the more than 5,000 products available in the database, similarly to Kurbucz (2023), we focus only on medical products (marked by six-digit codes, HS-6), which can be classified into eight product categories as follows[2]:

A: Medical test kits (*HS-6: 300215, 382100, 382200, 902780*);
B: Disinfectants and sterilization products (*HS-6: 220710, 220890, 284700, 300490, 380894, 841920*);
C: Other medical consumables (*HS-6: 280440, 300510, 300590, 300670, 340111, 340120, 392329, 392690, 481890, 901831, 901832*);
D: Other medical devices and equipment (*HS-6: 732490, 841319, 901811, 901812, 901890, 902212, 902519, 902780, 902820*);
E: Other medical-related goods (*HS-6: 731100, 761300, 842139, 940290*);
F: Oxygen therapy equipment and pulse oximeters (*HS-6: 901819, 901839, 901920, 902680*);
G: Protective garments (*HS-6: 392620, 401511, 401519, 401590, 481850, 611610, 621010, 621050, 621600, 630790, 650500, 900490, 902000*);

[1] It is freely available at the following: http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37 (accessed: 14 July 2023).

[2] The medical products and their categories are identified based on https://wits.worldbank.org/trade/covid-19-medical-products.aspx (accessed: 14 July 2023).

H: Vehicles (*HS-6: 870590, 871310, 871390*).

Exported values from the above-mentioned medical products are aggregated by product category for 2019 and 2020. In the following, for a given product category, the total exported values from country i to the country j in 2019 and 2020 are denoted by $\mathrm{EXP}_{i,j}^{2019}$ and $\mathrm{EXP}_{i,j}^{2020}$, respectively.

Extended Gravity database

The majority of the independent variables used in the analysis are obtained from the CEPII Gravity (Conte et al. 2022) database, which contains a wide range of uni- and bilateral variables related to international trade between 1948 and 2019.[3] From this database, economic and geographic indicators are collected for the year 2019. According to Kurbucz (2023), the traded values of the investigated medical products are highly correlated with the innovation capacity of the countries; thus, we complement these data with data drawn from the Global Innovation Index (GII) (Soumitra et al. 2020), which aims to capture the multidimensional aspects of innovation.[4] Note that indicators with a higher absolute Pearson correlation coefficient than 0.8 are not included together in the final model.

COVID-19 database

Data on COVID-19 cases and deaths are collected from the WHO's COVID-19 Dashboard (COVID 2020).[5] For each country, we use the latest data available from 2020. Since data on cases and deaths are highly correlated, only the former is applied during the analysis.

Applied dataset

The dataset compiled using the three data sources (see the Data sources section) is presented in Table 1.

More information about the variables of the Gravity database can be found at http://www.cepii.fr/DATA_DOWNLOAD/gravity/doc/Gravity_documentation.pdf (accessed: 14 July 2023).

Multilevel network representation

The trading data is represented as a multilevel network (see,e.g., (Hammoud and Kramer 2020)). Multilevel networks include multiple layers that can contain a subset of all available nodes and edges. In our case, the eight product categories form eight layers, nodes are the countries, and directed edges represent their trading activities from the given product category. The weight of the edges within a product category is determined based on the difference between the values exported in 2020 and 2019 as follows:

[3] It is freely available at the following: http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=8 (accessed: 14 July 2023).

[4] It is freely available at the following: https://www.globalinnovationindex.org/ (accessed: 14 July 2023).

[5] It is freely available at the following: https://covid19.who.int/data (accessed: 14 July 2023).

Table 1 Applied dataset

Notation	Name	Description	Source
$\mathrm{EXP}_{i,j}^{2020}$	trade20	Total export from country *i* to country *j* in 2020 (thousand USD)†	(a)
$\mathrm{EXP}_{i,j}^{2019}$	trade19	Total export from country *i* to country *j* in 2019 (thousand USD)†	(a)
x_1	contig	1 for contiguity	(b)
x_2	rta	1 if the pair currently has an RTA	(b)
$z_{1,i}$	eu_o	1 if the origin is a EU member	(b)
$z_{1,j}$	eu_d	1 if the destination is an EU member	(b)
$z_{2,i}$	wto_o	1 if the origin is a WTO member	(b)
$z_{2,j}$	wto_d	1 if the destination is a WTO member	(b)
$z_{3,i}$	gdp_o	GDP (current USD)‡	(b)
$z_{3,j}$	gdp_d	GDP (current USD)‡	(b)
$z_{4,i}$	gii_o	GII (score)‡	(c)
$z_{4,j}$	gii_d	GII (score)‡	(c)
$z_{5,i}$	covid_case_o	All reported COVID-19 cases until the end of 2020‡	(d)
$z_{5,j}$	covid_case_d	All reported COVID-19 cases until the end of 2020‡	(d)
$d_{i,j}$	dist	Distance between the most important cities (in terms of population)‡	(b)

Remarks: †: Separate variable for each product category. ‡: Measured in logarithmic scale. (a): BACI dataset (Gaulier and Zignago 2010). (b): Gravity dataset (Conte et al. 2022). (c): Global Innovation Index (Soumitra et a.l 2020). (d): WHO COVID-19 Dashboard (COVID 2020)

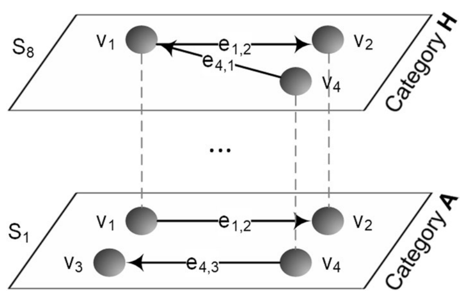

Fig. 1 Applied multilevel data structure. (Remarks: v_i: node *i*, $e_{i,j}$: edge from node *i* to *j*. Each $e_{i,j}$ edge has a $w_{i,j}$ weight.)

$$w_{i,j} = \mathrm{EXP}_{i,j}^{2020} - \mathrm{EXP}_{i,j}^{2019}, \tag{1}$$

where $\mathrm{EXP}_{i,j}^{2020}$ is the aggregated exported value from country i to j in 2020, measured in thousand United States dollars (USD), $i, j \in \{1, 2, \ldots, L\}$ and $L \in \mathbb{N}$.

Formally, the trading data is represented by a graph which is a tuple defined by the sets of nodes (N), edges (E), and eight layers (S) as follows:

$$\begin{aligned} \mathrm{G} &= (\mathrm{N}, \mathrm{E}, \mathrm{S}), \\ \mathrm{S} &= \{\mathrm{S}_1, \mathrm{S}_2, \ldots, \mathrm{S}_K\} \quad \text{sub-graphs} \\ \text{with} \quad \mathrm{S}_k &= (\mathrm{N}_k, \mathrm{E}_k),\ k \in \{1, 2, \ldots, K\}, \\ \mathrm{X} &= \bigcup_{k=1}^{K} \mathrm{N}_k, \quad \mathrm{E} = \bigcup_{k=1}^{K} \mathrm{E}_k, \end{aligned} \tag{2}$$

where $K = 8$. The applied multilevel data structure is illustrated in Fig. 1.

Centrality measures and other descriptive statistics

To measure the extent to which the products' total imported and exported values changed in each country between 2019 and 2020, the directed version of strength (i.e., weighted degree) centrality (see, e.g., (Yook et al. 2001; Barrat et al. 2004)) is applied. For each product category, the in- and out-strength centrality—measured in thousand USD—can be defined as follows:

$$s_i^{\mathrm{in}} = \sum_{j=1}^{L} e_{j,i} w_{j,i}, \qquad s_i^{\mathrm{out}} = \sum_{j=1}^{L} e_{i,j} w_{i,j}, \tag{3}$$

where $\sum_{j=1}^{L} e_{j,i}$ and $\sum_{j=1}^{L} e_{i,j}$ alone measure the in- and out-degree centrality of the node i, respectively.

In addition, to provide further details about the examined networks, we have also identified the strong and weak components of each layer. Strong components of a network are subsets of nodes where there is a directed path from any node to any other node within the subset, while weak components are subsets of nodes where there is a path (not necessarily directed) between any two nodes within the subset.

Regression model

The gravity equation of trade defines trade as a positive function of the attractive "mass" of two economies and a negative function of the distance between them (Lewer and Van den Berg 2008). Similarly to other researchers (see,e.g., (Johnston et al. 2015; Hussain et al. 2021; Fontagné et al. 2022)), we use additional variables to control for demographic, geographic, ethnic, linguistic, and economic conditions. For each product category, the applied regression model is as follows:

$$\begin{aligned}\log\left(EXP_{i,j}^{2020}\right) = \alpha_0 + \alpha_1 \log\left(EXP_{i,j}^{2019}\right) + \left(\sum_{p=1}^{P} \beta_p x_p\right) + \left(\sum_{r=1}^{R} \gamma_{r,i} z_{r,i} + \gamma_{r,j} z_{r,j}\right) \\ + \delta \log(d_{i,j}) + \epsilon_{i,j},\end{aligned} \tag{4}$$

where $P = 8$ and $R = 9$ are the numbers of uni- and bilateral independent variables (apart from $\log(EXP_{i,j}^{2019})$ and $dist_{i,j}$), respectively (see Table 1). The parameters, denoted by α, β, γ, and δ, are estimated by ordinary least squares (OLS) regression in which the $\epsilon_{i,j}$ is the random error term.

Applied software

The statistical programming language R is applied to compile and analyze the dataset presented in Table 1. To generate the figures and calculate the strength centrality measures, `MuxViz` (version: 3.1) R package (De Domenico et al. 2015; De Domenico 2022) is applied. This package enables the visualization and analysis of interconnected multilayer networks. More information can be found at https://github.com/manlius/muxViz (accessed: 14 July 2023).

Table 2 Descriptive statistics

Measures	Category A	Category B	Category C	Category D	Category E	Category F	Category G	Category H
Nodes	224	224	224	224	224	224	224	215
Edges	11,127	8,755	9,989	9,875	8,016	8,289	9,390	4,255
Weak components	1	1	1	1	2	1	1	10
Strong components	3	37	20	15	37	43	21	83
Average in- and out-degree c.	49.674	39.085	44.594	44.085	35.786	37.004	41.920	18.996
Average in- and out-strength c.	114,377.121	106,710.742	15,003.191	14,276.573	10,372.020	33,133.631	397,475.336	-8,208.204

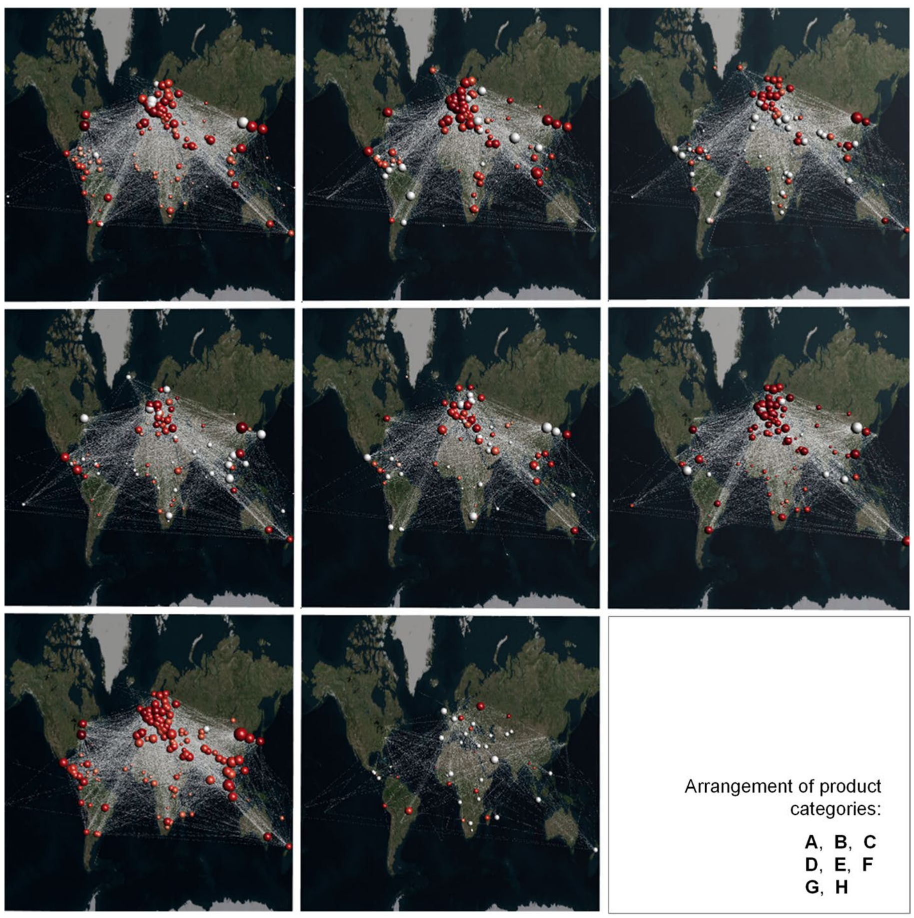

Fig. 2 Import and export growth of different product categories between 2019 and 2020. (Remarks: node color: $log(s_i^{in})$, from white to red, node size: $log(s_i^{out})$, from small to big.)

Results and discussion

Changes in the trade of medical products

Import and export growth between 2019 and 2020 is examined using in- and out-strength centrality measures, supplemented with other descriptive statistics that provide further insights into the investigated networks. First, these descriptive statistics are presented in Table 2, and then Fig. 2 illustrates the changes of the trade networks on a map.

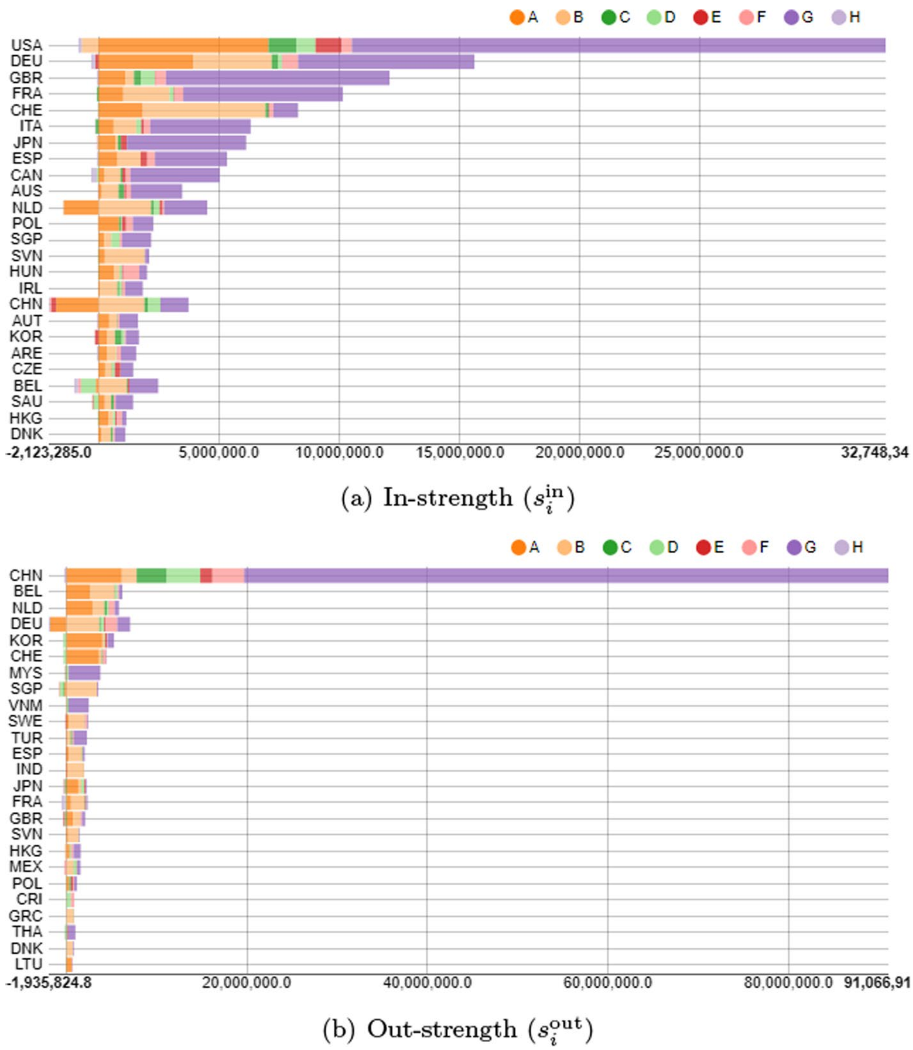

Fig. 3 In- and out-strength centralities of different product categories. (Remarks: Top 25 countries based on aggregated measurements. Weights are export differences between 2020 and 2019. Country codes can be found in the Appendix in Table A1.)

Figure 3 shows the twenty-five countries with the largest total import and export growth between 2019 and 2020 (i.e., the countries with the highest in- and out-strength centralities). Finally, the top five countries that have the largest import and export growth in each of the examined product categories are presented in Table 3 individually.

According to Fig. 3 and Tables 2 and 3, the traded value of protective garments (category **G**), medical test kits (category **A**), and disinfectants and sterilization products (category **B**) increased the most. China (CHN) alone increased its exports of protective garments (category **G**) by 71, 362, 502 thousand USD, which is approximately 20.38 times higher than the second-highest export growth in this product category, which was recorded in Malaysia (MYS). For these products, imports increased the most in the United States (USA), United Kingdom (GBR), and Germany (DEU)—22, 224, 368, 9, 287, 062, and 7, 321, 810 thousand USD, respectively; however, as Fig. 2 shows, most countries in the world had significantly increased imports of protective garments by 2020. In categories **A** and **B**, China (CHN) and Germany (DEU) achieved the highest

Table 3 Countries with the largest total import and export growth in each product category

Type	Rank	Category	A	B	C	D	E	F	G	H
Import	1	Country	USA	CHE	USA	USA	USA	HUN	USA	OMN
		Total growth	7,060,897	5,100,978	1,157,565	794,627	1,089,646	670,942	22,224,368	95,343
	2	Country	DEU	DEU	PHL	GBR	ESP	DEU	GBR	EGY
		Total growth	3,935,853	3,258,025	298,049	573,639	278,478	667,602	9,287,062	54,410
	3	Country	CHE	NLD	VNM	CHN	JPN	RUS	DEU	AFG
		Total growth	1,839,298	2,186,189	297,605	514,167	244,521	435,526	7,321,810	27,051
	4	Country	GBR	FRA	GBR	SGP	CZE	GBR	FRA	KAZ
		Total growth	1,115,849	1,919,581	288,030	334,525	234,930	433,852	6,629,931	18,611
	5	Country	FRA	CHN	KOR	RUS	POL	USA	JPN	RUS
		Total growth	1,028,087	1,907,719	281,602	251,042	173,745	421,239	4,952,549	16,478
Export	1	Country	CHN	DEU	CHN	CHN	CHN	CHN	CHN	ARE
		Total growth	6,155,374	3,664,058	3,329,381	3,708,636	1,346,074	3,522,334	71,362,502	67,694
	2	Country	KOR	SGP	NLD	CRI	POL	DEU	MYS	RUS
		Total growth	3,989,053	3,394,602	243,513	471,111	272,983	1 338,991	3,501,566	48,844
	3	Country	CHE	BEL	POL	DEU	PRT	NLD	VNM	BRA
		Total growth	3,643,297	2,709,908	190,187	377,339	206,341	623,043	2,229,284	27,985
	4	Country	NLD	IND	DEU	JPN	KOR	CRI	TUR	IRL
		Total growth	2,907,964	1,780,293	144,168	340,971	172,040	374,916	1,456,895	10,299
	5	Country	BEL	SWE	TUR	MEX	ZAF	NZL	DEU	NER
		Total growth	2,672,727	1,708,196	120,078	333,531	169,628	351,400	1,408,770	2,658

Remarks: Total import and export changes are defined by s_i^{in} and s_i^{out}, respectively. Both are measured in thousand USD. Country codes can be found in the Appendix in Table A1 export growth (6, 155, 374 and 3, 507, 406 thousand USD, respectively), while the highest import growths were recorded in the United States (USA) and Switzerland (CHE) (7, 060, 897 and 5, 100, 978 thousand USD, respectively).

The international trade of vehicles (category **H**) typically decreased during the investigated time period, and the related network was much more fragmented than that of other types of products (see Table 2). In this category, the highest export growth was only 67.694 thousand USD, which was reached by the United Arab Emirates (ARE). In the case of categories **C** to **F**, China (CHN) achieved the largest increase in exports by 3, 329, 381, 3, 708, 636, 1, 346, 074, and 3, 522, 334 thousand USD, respectively. While the highest import growth was recorded in the United States (USA) from categories **C** to **E** (1, 157, 565, 794, 627, 1, 089, 646 thousand USD, respectively), despite its population of only 9.7 million, Hungary (HUN) achieved the largest increase in imports of oxygen therapy equipment and pulse oximeters (category **F**) by 670, 942 thousand USD. This import growth is related to the Hungarian government's procurement of more than 16, 000 ventilators from China (CHN).[6]

After aggregating each product category (see Fig. 3), it can be seen that China (CHN) achieved the largest export growth by 90, 833, 770 thousand USD, which is approximately 14.66 times higher than the second-highest cumulative export growth (6, 194, 989 thousand USD), which was recorded in Belgium (BEL). In the case of aggregate import growth, there was no such degree of asymmetry between the top two countries, which were the United States (USA) and Germany (DEU) by 31, 853, 163 and 15, 268, 697 thousand USD, respectively.

Regression results

The results of the regression analysis are presented in Table 4.

Based on the results, it can be seen that the global F-test was highly significant for all models, while the adjusted R^2 values varied between 0.199 and 0.805. This difference in adjusted R^2 mainly reflects the stability of trade relations (network structure) between 2019 and 2020. Thus, e.g., the highest adjusted R^2 was observed for medical test kits (category **A**), in which the logarithm of the 2019 and 2020 trading values had the highest Pearson correlation coefficient ($\rho = 0.873$). Regardless of product category, the significant values of RTA and the EU membership of the exporter countries increased the traded value, while the effect of the EU membership was shown to be the opposite on the importer's side. The coefficients of WTO membership were only slightly significant. While they were typically positive on the importer's side, the sign of the effect varied in the case of exporting countries. The GDP of both the exporter and importer countries increased the traded value, while the coefficient of the exporter countries was approximately 1.5–2.0 times greater than the coefficient of the importer countries.

Cumulative COVID-19 cases were significant in only half of the categories and typically reduced trade value, regardless of whether they were measured for exporting or importing countries. An exception to this was the disinfectants and sterilization products (category **C**), in which the higher COVID-19 cases in exporter countries typically increased

[6] More information about this procurement can be found at https://hungarianspectrum.org/2020/06/30/hungary-the-ventilator-superpower/ (accessed: 14 July 2023) and https://www.direkt36.hu/en/a-kormany-dicsekedett-a-lelegeztetogepek-vasarlasaval-megis-ok-kotottek-a-legrosszabb-uzletet-kinaval-az-egesz-eu-bol/ (accessed: 14 July 2023).

Table 4 Regression results

Variable	Category A		Category B		Category C		Category D		Category E		Category F		Category G		Category H	
(Intercept)	-9.816	***	-12.580	***	-17.941	***	-23.126	***	-20.348	***	-29.274	***	-16.472	***	-9.938	***
trade19	0.738	***	0.116	***	0.164	***	0.119	***	0.214	***	0.194	***	0.285	***	0.170	***
contig	0.225	.	1.258	***	0.682	*	0.815	**	0.821	**	0.909	***	0.572	.	0.781	*
rta	0.167	**	0.587	***	0.780	***	0.391	**	0.321	*	0.359	**	0.143		0.155	
eu_o	0.154	**	0.138		0.259		0.225		0.508	***	0.154		0.366	*	0.654	**
eu_d	-0.092		-0.500	*	-0.673	***	-0.173		-0.169		-0.456	**	0.236		0.110	
wto_o	-0.166		0.473		0.981	*	-0.792	*	-0.845	*	0.554		0.825	*	-0.941	
wto_d	0.062		0.067		0.365		-0.239		0.479	*	0.093		0.627	*	0.414	
gdp_o	0.352	***	0.468	***	0.931	***	0.775	***	0.858	***	0.853	***	1.147	***	0.723	***
gdp_d	0.204	***	0.363	***	0.474	***	0.581	***	0.636	***	0.667	***	0.567	***	0.444	***
gii_o	1.168	***	1.411	***	0.362		1.927	***	0.589	*	2.441	***	-1.613	***	-0.538	
gii_d	-0.220	*	-0.328		0.318		-0.308		-0.240		-0.078		0.365		0.314	
covid_case_o	-0.012		0.108	*	-0.158	***	-0.053		0.023		-0.117	***	-0.300	***	-0.131	*
covid_case_d	-0.024		-0.020		-0.070	.	-0.043		-0.085	*	-0.010		-0.059		-0.125	*
dist	-0.314	***	-0.633	***	-0.950	***	-0.497	***	-0.774	***	-0.606	***	-0.904	***	-0.659	***
R^2_{adj}	0.805		0.199		0.319		0.329		0.390		0.426		0.342		0.261	
F-test	***		***		***		***		***		***		***		***	
n	5851		2255		2291		2214		2481		2770		2390		1032	

the traded value. Based on these coefficients, the COVID-19 cases recorded in the exporting countries reduced the traded value of protective garments (category **G**) the most. In addition, the GII score of the exporting countries significantly reduced the trading value only in this product category. This result reflects that the production of protective garments (category **G**) had significantly lower technological demands than other investigated product categories. Finally, the contiguity of countries increased the traded value the most in the case of disinfectants and sterilization products (category **B**). After we controlled for this factor, the trade of medical test kits (category **A**) was the least distance-dependent category, while the distance between trading countries reduced the trade value of other medical consumables (category **C**) and protective garments (category **G**) the most.

Conclusions and future work

In this work, we investigated how and for what reasons the world trade networks of medical products were reorganized during the COVID-19 pandemic. To do so, we first collected the trade data of eight COVID-19-related product categories for the years 2019 and 2020. Afterward, with the help of the strength centrality measure, we examined which countries' exports and imports by product category changed the most between the examined periods. Finally, we used gravity models containing additional economic, geographic, and COVID-19-related variables to analyze the impact of the pandemic on the investigated trade networks.

In line with the descriptive statistics, China achieved the largest cumulative export growth of 90, 833, 770 thousand USD, which is approximately 14.66 times higher than the second-highest cumulative export growth (6, 194, 989 thousand USD), which was recorded in Belgium. The dramatic increase in Chinese exports comes primarily from the sale of protective garments (71, 362, 502 thousand USD). In the case of aggregate import growth, there was no such degree of asymmetry between the top importer countries. In addition, with a population of only 9.7 million, Hungary stands out among the main importers of medical products by purchasing more than 16, 000 ventilators from China.

According to the results of the regression analysis, the structure of the trade network changed the least in the case of medical test kits. Regardless of product category, the significant values of RTA and the EU membership of the exporter countries increased the traded value, while this effect was shown to be the opposite on the importer's side. The trade of protective garments was the most sensitive to the number of COVID-19 cases in the exporting countries. Furthermore, the GII score of the exporting countries significantly reduced the trading value only in this product category.

Based on our results, further examination of the trade networks—e.g., by focusing on the ego networks of key exporters and importers—could reveal important details related to the effect of COVID-19 on the global economy in more areas than the case of medical products investigated herein. In addition, the longer-term investigation and comparison of trade networks could show not only the effect of the COVID-19 pandemic but also the consolidation of trade relations in the post-COVID-19 era.

Appendix

See Table 5.

Table 5 Country codes

Code	Name	Code	Name	Code	Name
ABW	Aruba	GEO	Georgia	NLD	Netherlands
AFG	Afghanistan	GHA	Ghana	NOR	Norway, Svalbard and Jan Mayen
AGO	Angola	GIB	Gibraltar	NPL	Nepal
AIA	Anguilla	GIN	Guinea	NRU	Nauru
ALB	Albania	GMB	Gambia	NZL	New Zealand
AND	Andorra	GNB	Guinea-Bissau	OMN	Oman
ARE	United Arab Emirates	GNQ	Equatorial Guinea	PAK	Pakistan
ARG	Argentina	GRC	Greece	PAN	Panama
ARM	Armenia	GRD	Grenada	PER	Peru
ASM	American Samoa	GRL	Greenland	PHL	Philippines
ATF	French South Antarctic Territories	GTM	Guatemala	PLW	Palau
ATG	Antigua and Barbuda	GUM	Guam	PNG	Papua New Guinea
AUS	Australia	GUY	Guyana	POL	Poland
AUT	Austria	HKG	China, Hong Kong Special Administrative Region	PRK	Democratic People's Republic of Korea
AZE	Azerbaijan	HND	Honduras	PRT	Portugal
BDI	Burundi	HRV	Croatia	PRY	Paraguay
BEL	Belgium	HTI	Haiti	PSE	State of Palestine
BEN	Benin	HUN	Hungary	PYF	French Polynesia
BES	Bonaire, Saint Eustatius and Saba	IDN	Indonesia	QAT	Qatar
BFA	Burkina Faso	IND	India	ROU	Romania
BGD	Bangladesh	IOT	British Indian Ocean Territories	RUS	Russian Federation
BGR	Bulgaria	IRL	Ireland	RWA	Rwanda
BHR	Bahrain	IRN	Iran	SAU	Saudi Arabia
BHS	Bahamas	IRQ	Iraq	SDN	Sudan
BIH	Bosnia Herzegovina	ISL	Iceland	SEN	Senegal
BLM	Saint-Barthélemy	ISR	Israel	SGP	Singapore
BLR	Belarus	ITA	Italy	SHN	Saint Helena
BLZ	Belize	JAM	Jamaica	SLB	Solomon Islands
BMU	Bermuda	JOR	Jordan	SLE	Sierra Leone
BOL	Plurinational State of Bolivia	JPN	Japan	SLV	El Salvador
BRA	Brazil	KAZ	Kazakhstan	SMR	San Marino
BRB	Barbados	KEN	Kenya	SOM	Somalia
BRN	Brunei Darussalam	KGZ	Kyrgyzstan	SPM	Saint Pierre and Miquelon
BTN	Bhutan	KHM	Cambodia	SRB	Serbia
BWA	Botswana	KIR	Kiribati	SSD	South Sudan
CAF	Central African Republic	KNA	Saint Kitts and Nevis	STP	Sao Tome and Principe
CAN	Canada	KOR	Republic of Korea	SUR	Suriname
CCK	Cocos Islands	KWT	Kuwait	SVK	Slovakia
CHE	Switzerland, Liechtenstein	LAO	Lao Peoples Dem. Rep.	SVN	Slovenia
CHL	Chile	LBN	Lebanon	SWE	Sweden
CHN	China	LBR	Liberia	SWZ	Swaziland
CIV	Côte d'Ivoire	LBY	Libya	SXM	Saint Maarten (Dutch part)
CMR	Cameroon	LCA	Saint Lucia	SYC	Seychelles
COD	Democratic Republic of the Congo	LKA	Sri Lanka	SYR	Syria
COG	Congo	LSO	Lesotho	TCA	Turks and Caicos Islands

Table 5 (continued)

Code	Name	Code	Name	Code	Name
COK	Cook Islands	LTU	Lithuania	TCD	Chad
COL	Colombia	LUX	Luxembourg	TGO	Togo
COM	Comoros	LVA	Latvia	THA	Thailand
CPV	Cabo Verde	MAC	China, Macao Special Administrative Region	TJK	Tajikistan
CRI	Costa Rica	MAR	Morocco	TKL	Tokelau
CUB	Cuba	MDA	Republic of Moldova	TKM	Turkmenistan
CUW	Curaçao	MDG	Madagascar	TLS	Timor-Leste
CXR	Christmas Islands	MDV	Maldives	TON	Tonga
CYM	Cayman Islands	MEX	Mexico	TTO	Trinidad and Tobago
CYP	Cyprus	MHL	Marshall Islands	TUN	Tunisia
CZE	Czechia	MKD	The Former Yugoslav Republic of Macedonia	TUR	Turkey
DEU	Germany	MLI	Mali	TUV	Tuvalu
DJI	Djibouti	MLT	Malta	TZA	United Republic of Tanzania
DMA	Dominica	MMR	Myanmar	UGA	Uganda
DNK	Denmark	MNE	Montenegro	UKR	Ukraine
DOM	Dominican Republic	MNG	Mongolia	URY	Uruguay
DZA	Algeria	MNP	Northern Mariana Islands	USA	USA, Puerto Rico and US Virgin Islands
ECU	Ecuador	MOZ	Mozambique	UZB	Uzbekistan
EGY	Egypt	MRT	Mauritania	VCT	Saint Vincent and the Grenadines
ERI	Eritrea	MSR	Montserrat	VEN	Venezuela
ESP	Spain	MUS	Mauritius	VGB	British Virgin Islands
EST	Estonia	MWI	Malawi	VNM	Viet Nam
ETH	Ethiopia	MYS	Malaysia	VUT	Vanuatu
FIN	Finland	NAM	Namibia	WLF	Wallis and Futuna Islands
FJI	Fiji	NCL	New Caledonia	WSM	Samoa
FLK	Falkland Islands (Malvinas)	NER	Niger	YEM	Yemen
FRA	France, Monaco	NFK	Norfolk Islands	ZAF	South Africa
FSM	Federated State of Micronesia	NGA	Nigeria	ZMB	Zambia
GAB	Gabon	NIC	Nicaragua	ZWE	Zambia
GBR	United Kingdom	NIU	Niue		

Abbreviations

COVID-19	Novel coronavirus
EU	European Union
GII	Global Innovation Index
GNI	Gross national income
HS-6	Six-digit harmonized system codes
OLS	Ordinary least squares
USD	United States dollar
RTA	Regional trade agreement
WHO	World Health Organization
WTO	World Trade Organization

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M.T.K., A.S., and T.K. designed the study and conducted the literature review. M.T.K. collected and cleaned the data and performed the analysis. All authors were involved in writing and reviewing the paper.

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Availability of data and materials
The BACI international trade database (Gaulier and Zignago 2010) is freely available at the following: http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37 (accessed: 14 July 2023). The CEPII Gravity (Conte et al. 2022) database is freely available at the following: http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=8 (accessed: 14 July 2023). The GII (Soumitra et al. 2020) is freely available at the following: https://www.globalinnovationindex.org/ (accessed: 14 July 2023). The WHO's COVID-19 Dashboard (COVID 2020) is freely available at the following: https://covid19.who.int/data (accessed: 14 July 2023).

Declarations

Competing Interests
The authors declare that they have no competing interests.

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