Vaccine Distribution Optimization:
Preparing for the Next Pandemic

DSKUS Group 6
Carolyn Haythorn
Sneha Satish
Haneul Kim
Yeeun Jeon

Introduction
Our group was assigned the topic, “Mitigating disruptions in the global supply chain caused by the continued COVID-19 pandemic.’’ Global supply chain management incorporates the range of activities coordinated by disparate organizations around the globe to procure and manage supplies, and involves all parties that directly or indirectly fulfill a customer request [1]. As the world witnessed in 2020, the global supply chain can be fragile, especially in the face of unprecedented interruptions, such as the COVID-19 pandemic. As different countries enacted their own containment and mitigation strategies [2], supply chain bottlenecks and shuttered manufacturing sites lead to shortages of consumer goods, or even vital medical supplies such as personal protective equipment and medications.

As the pandemic lingered, experts emphasized the importance of preferentially recovering from COVID-19 in order to mitigate disruptions in the global supply chain. Health experts named the development of a vaccine as a crucial factor to accelerate COVID-19 recovery. In order to mitigate disruptions in the global supply chain by the continued COVID-19 pandemic, the recovery from COVID-19 by vaccine distribution was crucial.

In 2023, many countries have recovered from COVID-19. The mandatory wearing of masks has been removed and online meetings have transferred to in-person meetings. Considering the world trend related to COVID-19, the assigned topic seemed out of date. So our group specified the project topic as “Optimizing vaccine distribution in future pandemic situations.”

How were vaccines distributed during COVID-19? Unequal vaccine distribution undoubtably prolonged the COVID-19 pandemic. The explosive global spread of COVID-19 pandemic generated international consensus in principle, between the World Health Organization (WHO), vaccine developers, governments, funders, donors and industry, with agreement on the need to develop an effective COVID vaccine and plans for fair and equitable rollout to all countries. However, richer nations focused on being the first to develop and roll out COVID-19 vaccines to their own populations, rather than focus on what was best for all of humanity. An international panel of medical professionals concluded, “The emergence of the Omicron variant and its rapid spread reflects the legacy of wealthy nations’ failure to equitably distribute COVID-19 vaccines globally. This failure also contributed to prolonging the pandemic and placed the whole world at continued risk of COVID-19 and continuing impact on their economies” [3]. According to the McKinsey Institute, “as of July 2022, only 24.4 percent of the population had received at least one dose, compared with the global average of 69.0 percent.”[1] “Tragically, concerns regarding access to COVID-19 vaccines in Africa are similar to those raised during the HIV pandemic in the mid-1990s and early 2000s, when highly active antiretroviral treatment (HAART) was accessible in high-income countries but was too expensive for rollout in African countries - a disparity that resulted in many preventable deaths in these high-burden settings” [4].

Equal vaccine distribution will lead to public health benefits and curb the spread of additional viruses globally. If High Income Countries (HICs) donate a certain portion of their vaccine supplies to Low- or Middle-Income Countries (LMICs) instead of vaccinating their entire population as the top priority, enormous public health benefits can be seen for both HICs and LMICs. Furthermore, for HICs, donating a small portion of vaccines to LMICs could lower the risk of future waves impacting their own countries in the future. Additionally, donating vaccines to more LMICs rather than only directly neighboring LMICs is more efficient in curbing the spread of the virus [5].

Although the COVID-19 pandemic has ended, there is still enormous potential to learn from experience in order to mitigate disruptions to the global supply chain caused by future pandemics. As we could see that unequal vaccine distribution leads to slow recovery in past pandemics, for future pandemics, equal vaccine distribution is needed. In this project, using country-level datasets (country-wise population data, secured or expected vaccine amounts data, country distance data, country trade data), our goal is to display vaccine related information in the dashboard and build an algorithm that makes equal vaccine distribution between countries based on COVID-19 data.

Literature Review

Much research has been carried out in the field of vaccine distribution optimization problems and there were various views about dealing with this problem. One paper proposed a robust bi-level optimization model to address the hurdles in the public vaccination program according to the concerns of the government and the organizations

[1]Chen, Kaplow, Onabanjo, and Sunny Sun, “A data-driven approach to addressing COVID-19 vaccine uptake in Africa” *McKinsey & Company,* 2 August 2022. Accessed online.

involved [6]. At the upper level, the risk of mortality due to the untimely supply of the vaccine and the risk of inequality in the distribution of the vaccine is considered. All costs related to the vaccine supply chain are considered at the lower level, including the vaccine supply, allocation of candidate centers for vaccine injection, cost of maintenance and injection, transportation cost, and penalty cost due to the vaccine shortage. In addition, the uncertainty of demand for vaccines is considered with multiple scenarios of different demand levels. The results show that the proposed model significantly reduces the risk of mortality and inequality in the distribution of vaccines as well as the total cost, which leads to managerial insights for better coordination of the vaccination network during the COVID-19 pandemic

.

Another paper studies an integrated two-phase planning framework for the vaccine distribution network [7]. In the first phase, the population target is classified into several groups to determine their priority for vaccination using a multiple attribute decision making (MADM) technique. The second phase uses a mathematical model to decide on the location of distribution centers, inventory policies, and routing decisions to minimize the total procurement, inventory, and distribution costs.

Also there was a paper presenting hybrid machine learning and evolutionary computation methods [8]. Researchers first used a fuzzy deep learning model to forecast the demands for vaccines for each next day, to redistribute the forecasted number of vaccines to the satellites in advance; after obtaining the actual demands, used an evolutionary algorithm (EA) to route vehicles to distribute vaccines from the satellites/depots to the inoculation spots on each day. The EA saves historical problem instances and their high-quality solutions in a knowledge base, so as to capture inherent relationship between evolving problem inputs to solutions; when solving a new problem instance on each day, the EA utilizes historical solutions that perform well on the similar instances to improve initial solution quality and, hence, accelerate convergence. Computational results on real-world instances of vaccine distribution demonstrate that the proposed method can produce solutions with significantly shorter distribution time compared to state-of-the-art medical programs and, hence, contribute to accelerating the achievement of herd immunity.

COVID 19 vaccines and treatment

The global pharmaceutical industry is committed to working together with governments and industry to increase production to meet the international community’s top priority of overcoming COVID-19 and ensuring the world has the vaccines patients need. Also they are focused on research and development based global collaboration to develop vaccines and therapeutics, including by continuing to advance science and innovation, collaborating on R&D, investing in new people and technologies. Global pharmaceutical companies have been at the forefront of the rapid domestic rollout of COVID-19 vaccines and treatments. They have also worked with governments to secure unprecedented emergency use authorizations for oral COVID-19 treatments for patient populations that need them more quickly. As a result, as of April 2023, more than 250,000 people with COVID-19 are being treated with oral treatments. As of April 25, 2022, a total of 11 vaccines and therapies have been granted Emergency Use Authorizations (EUAs) and licenses in the U.S.153 global vaccines are in clinical trials, and 557 global therapies are currently in clinical trials, with a total of 1,664 related trials. Innovative bio companies have been at the forefront of efforts to develop and manufacture safe and effective COVID-19 vaccines and treatments. Today, more than 12 billion doses of vaccine have been produced, and more than 65% of the world's population has received at least one dose of vaccine.

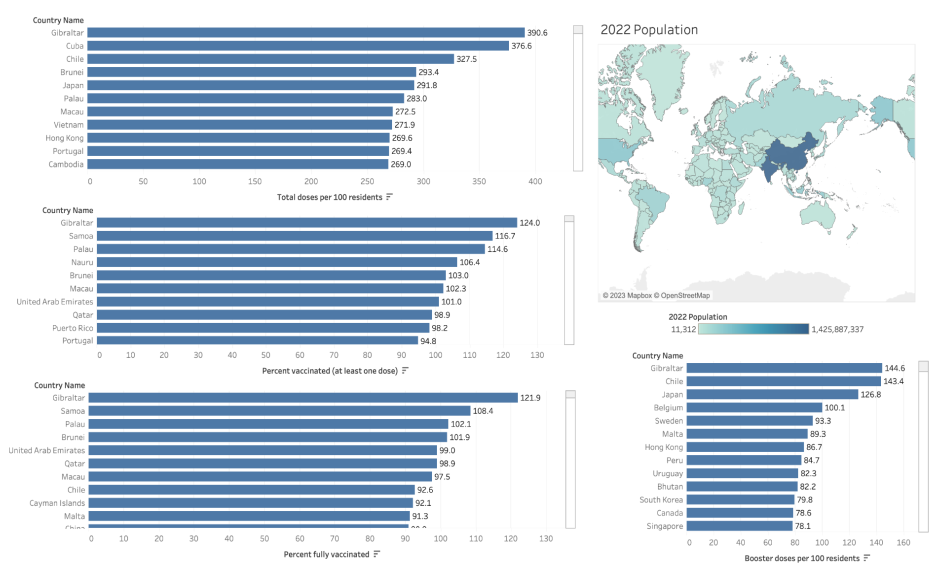
During the pandemic, global pharmaceutical companies quickly partnered with other manufacturers to supply COVID-19 vaccines around the world, and these partnerships have been key to increasing manufacturing and distribution capacity and ensuring patients have access to treatments and vaccines.[10] Global pharmaceutical companies have also entered into a number of global partnerships to increase access to COVID-19 treatments in low- and middle-income countries.

Exploratory Data Analysis

Our group started with exploratory data analysis to investigate the relationship between vaccines and global trade data. We were curious about how the COVID-19 pandemic impacted specific types of exports as well as the relationship between country vaccination rates and gross-domestic-product (GDP). In this section, we summarize our findings.

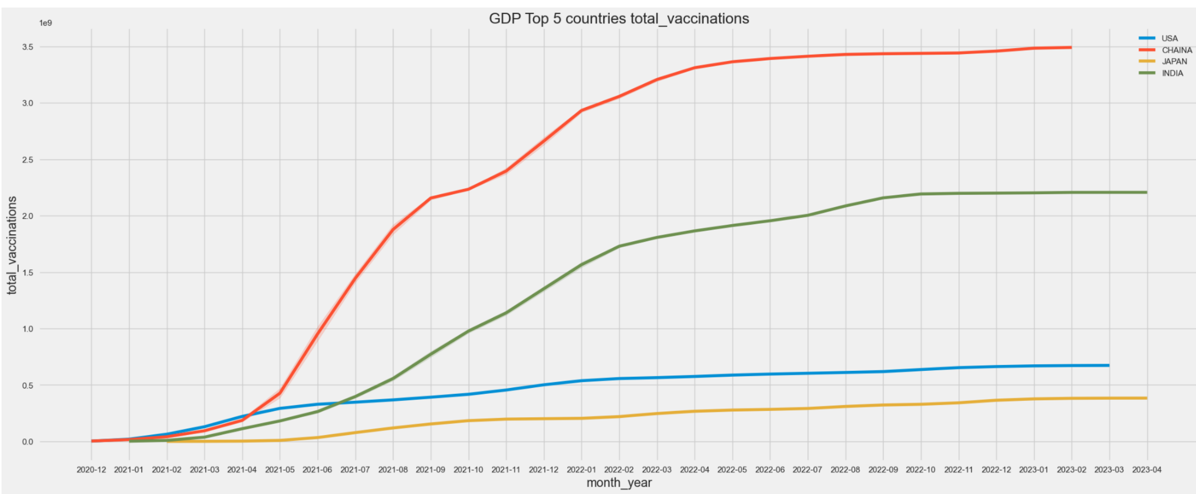
<u>Country Population, Vaccination Data, and Gross Domestic Products</u>

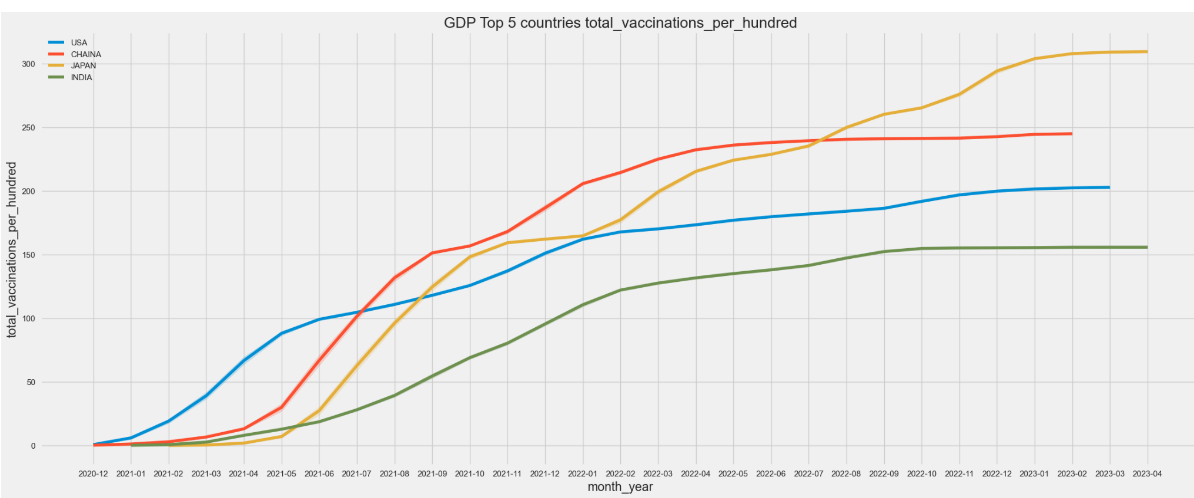
We first examined country population and vaccination data from the World Bank and the *Financial Times* "Covid-19 vaccine tracker: the global race to vaccinate". The dataset contains various vaccine related information for the year 2022 like the total dose per 100 residents, percent of people who are



vaccinated with at least one dose, percent of people who are fully vaccinated and the booster doses per 100 residents. There is also a heatmap which shows the 2022 population where the darker color signifies higher population. We visualized the information using a Tableau dashboard, above. The data show that China and India are the most populous countries, and Gibraltar has the highest portion of residents vaccinated.

Next, we compared the vaccination rates between the countries with the top five largest and smallest Gross Domestic Product (GDP). The top ranking counties are the USA, China, Japan, Germany, India. China had the largest number of vaccinations, followed by India, Japan, and the USA. However, when adjusted for population size, the ranking was Japan, China, the United States, and Germany.



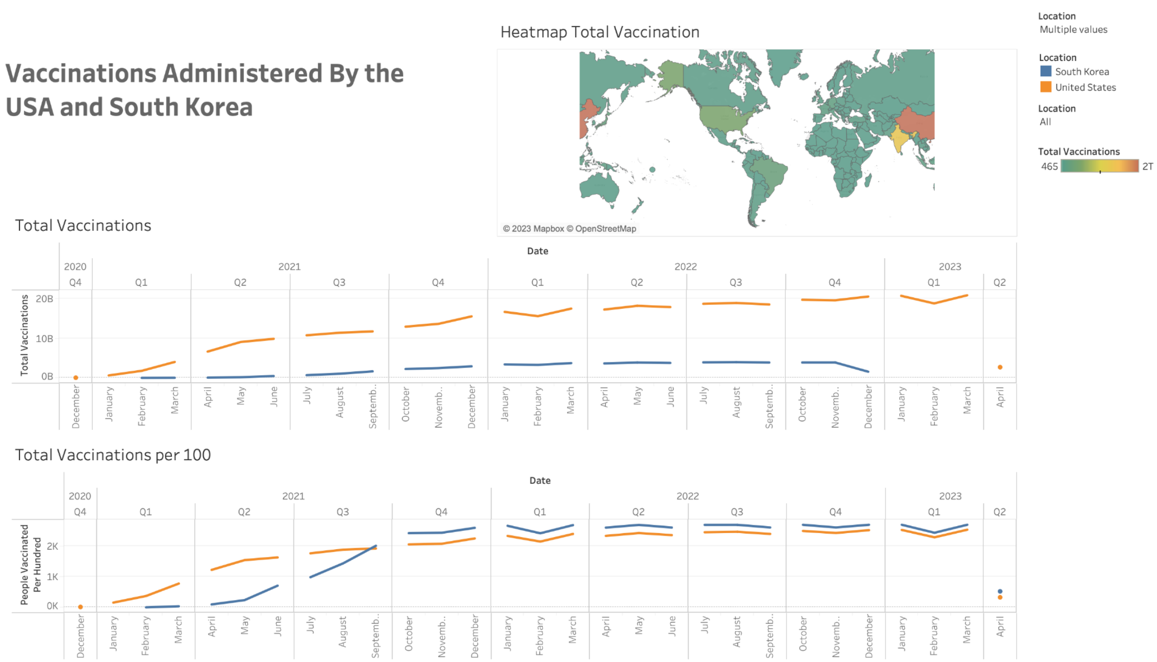


The countries with the lowest GDP are Estonia, Nepal, Paraguay, Bahrain, and Bolivia. Of those countries, Nepal had the most vaccines, followed by Bolivia, Paraguay, Bahrain,and Estonia.

Finally, we compared the USA and Korean vaccination rates using the “Covid

Vaccination in the World" dataset, which is updated daily, collected from Our world in Data (OWID) Github repository.

The geospatial heat map and top temporal visualization show the total vaccinations received in South Korea (blue) and United States (Orange) from December 2020 to April 2023. With the Geospatial heat map, where the darker color represents a higher number of vaccinations administered and the lighter represents a lower number of vaccinations administered. The bottom temporal visualization shows the total vaccinations administered per 100 persons received in South Korea (blue) and United States (Orange). We found that although more vaccinations have been administered in the U.S., Korea has a slightly higher per capita vaccination rate.



Korean Export and Vaccination Data

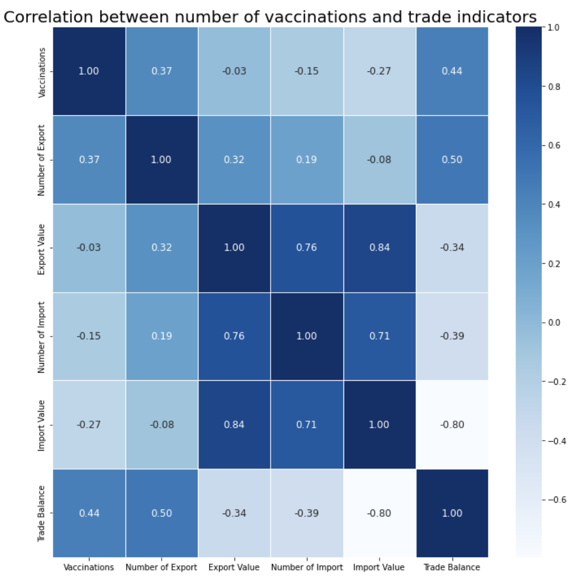
Using the Trade Statistics published by the Korean Customs Service, we compiled a dataset of the top 20 trade surplus items each month, from January 2020 - December 2022. For the time period examined, electronic integrated circuits, cars, and petroleum oil had the largest overall trade surplus (called positive trade balance). We plotted the total surplus of the items by month and found that April and May 2020 had the lowest overall trade surplus. This aligns with the time period when the lockdowns were first put in place and were most severe. After that, the trade surplus gradually increases, to a peak in March 2022.

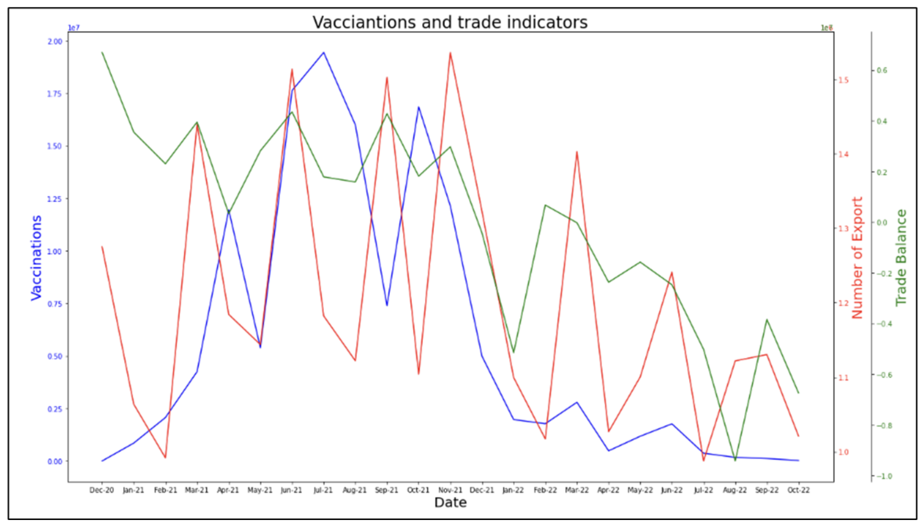
Positive Trade Balance: Top 10 Items

Item	Total Trade Balance (Thousands USD)
Electronic Integrated Circuits	$152,011,018
Cars	$92,588,241
Petroluem Oil	$59,179,931
Large Ships	$41,469,331
Car Parts	$41,437,733
CDs / Sound storage	$30,059,038
Machine Parts	$24,326,535
Cyclic Hydrocarbons	$20,100,052
Beauty and Skincare Products	$17,743,667
Flat Panel Displays	$16,658,028

For the second part of this analysis, we collected vaccination data from Kaggle and trade data from Korea Customs Service and combined the datasets between December 2020 to February 2023. We then calculated the correlation between vaccinations and trade indicators. We decided to use Pearson's correlation coefficient, which has a value between +1 and -1 by the Cauchy-Schwarz inequality, where +1 is perfect positive linear correlation, 0 is no linear correlation, and -1 is perfect negative linear correlation. And if the value is over than 0.3, it indicates that the two data are correlated. As you can see from the heat map, we found that the number of exports and the trade balance were above 0.3, indicating that there is a positive correlation with vaccinations.

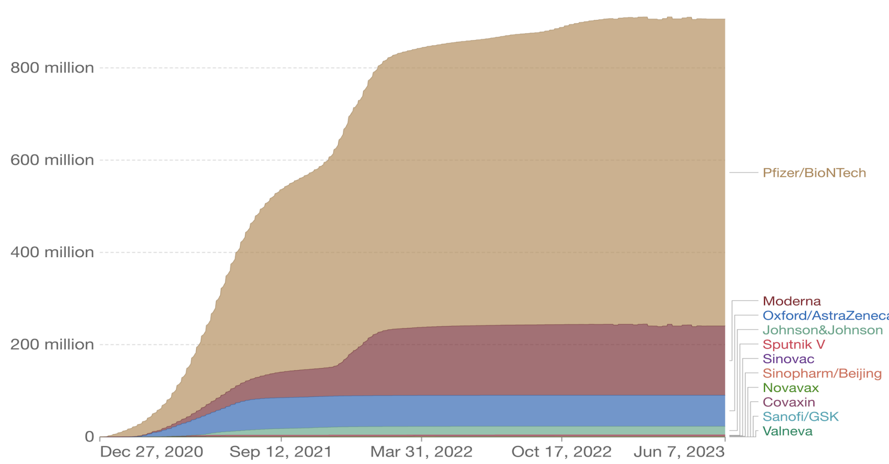
By plotting the line graph below, we see that in 2021 as the number of vaccinations increased, the number of exports also tended to increase, and in 2022, as the number of vaccinations decreased, exports and trade balance also decreased. Therefore, these results showed that the number of vaccinations is related to exports.



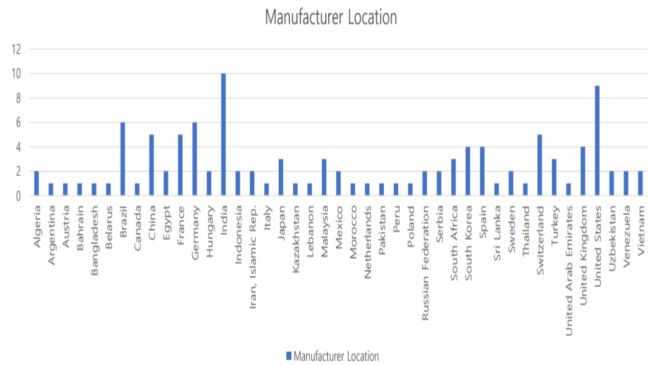


Vaccine Manufacturing Data

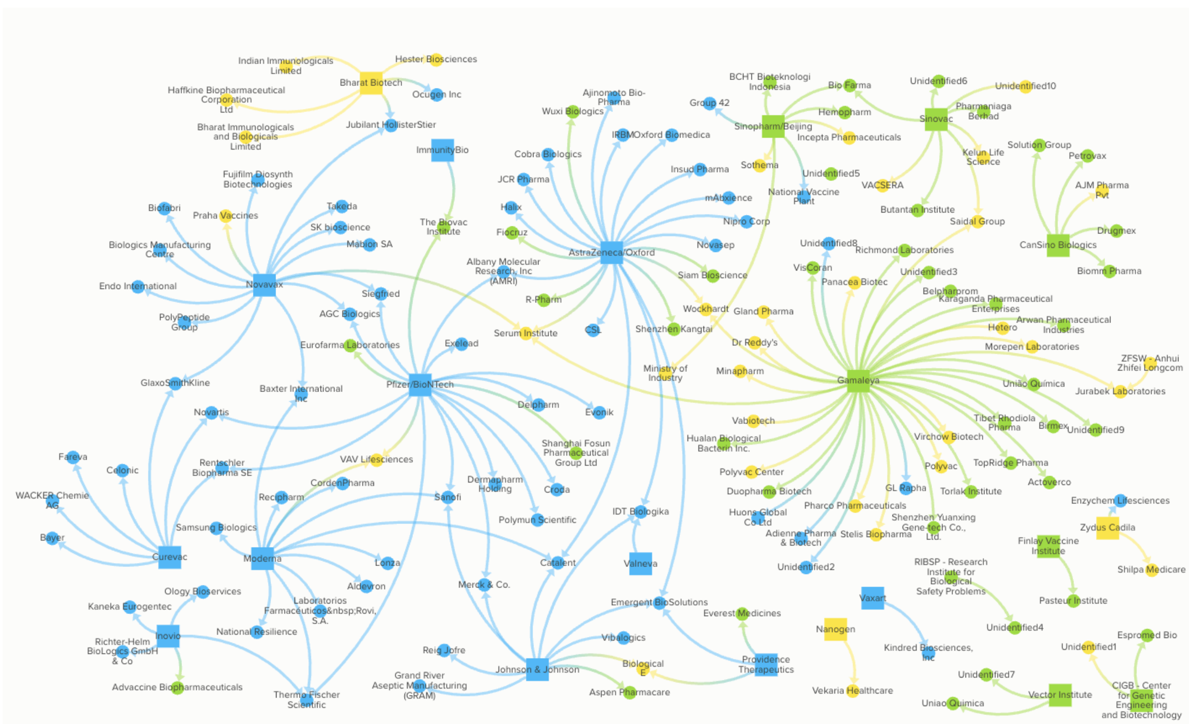
Next we looked at vaccine manufacturing data. The first dataset tracked the location of vaccine manufacturers and the number of doses of each vaccine type they produced. We see that Pfizer/BioNTech was the most widely produced vaccine, followed by Moderna and Oxford/AstraZeneca. We also see that the United States and China had the



most vaccine developer location, while India and the United States had the most manufacturer locations.

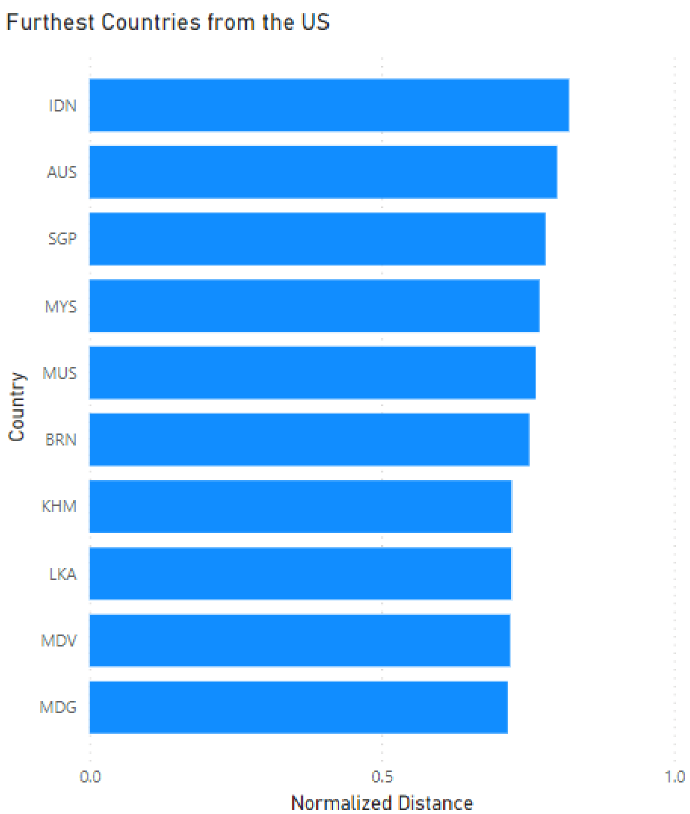


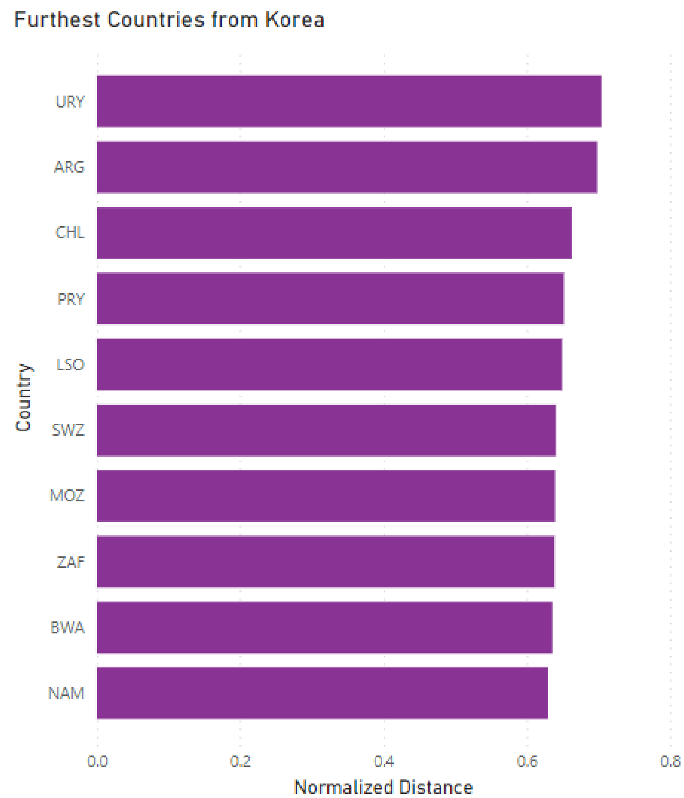
Finally, we found that vaccine developers based in high-income countries have primarily selected manufacturing partners also based in high income countries (79%, 77/97) . In contrast, vaccine developers from middle income countries (China, Cuba, India, Kazakhstan, Russia and Vietnam) have primarily selected manufacturing partners based in middle income countries (86%, 63/73; 42% lower-middle, 44% upper-middle). There are no arrangements in our dataset with manufacturers based in low-income countries.



Country Distance Data

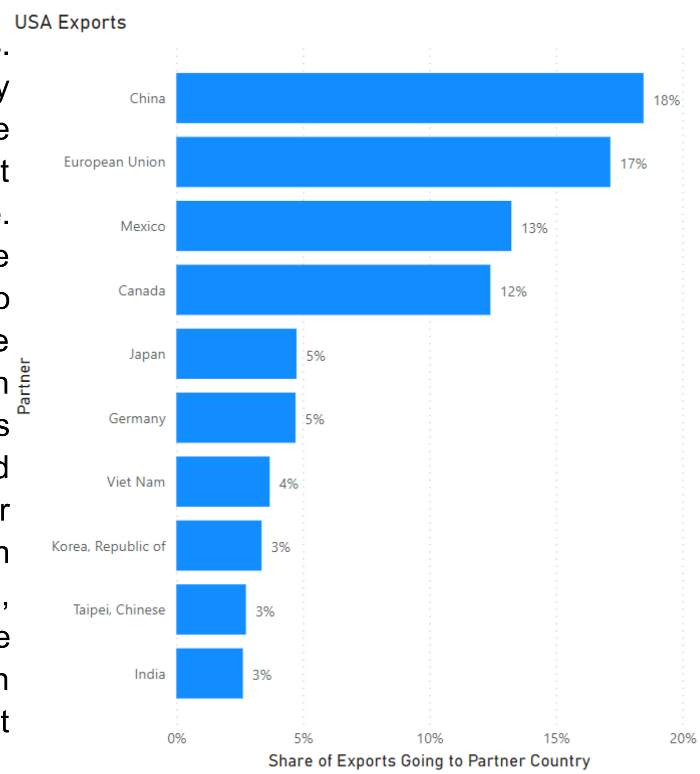
Next, we sought information on the distance between different countries. Utilizing data maintained by CEPHII, we found the distance between all countries. As a test, we identified the furthest countries from the United States and Korea. The furthest countries from the United States are Indonesia, Australia, and Singapore, and the furthest from Korea are Uruguay, Argentina, and Chile.

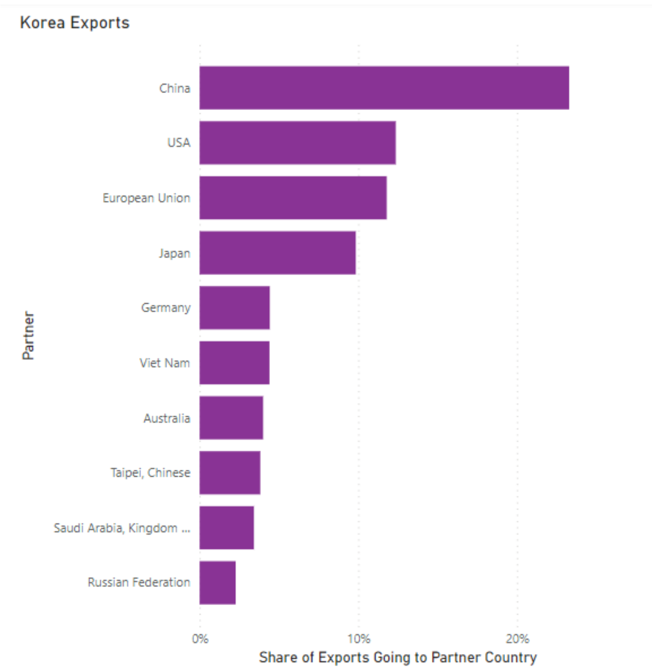




Country Relationships: Trade Data

Finally, we explored country relationships. Although we wanted to include country political relationships in our model, we were unable to find a suitable dataset during our data exploration phase. Instead, we pivoted to focus on the amount of trade shared between two countries utilizing data maintained by the World Trade Organization. Below you can see the top export countries for goods coming from the United States and Korea. China is the top export location for both countries, while the European Union is second and third for the US and Korea, respectively. The United States is the second most common export destination for Korea, while Korea is the eighth most common for the United States.





Final Data Sets and Data Cleaning

After data exploration, we landed on four primary datasets for our model:

1) *Country populations.* This is a list of all countries and their 2022 populations.
2) *Secured or Expected Vaccine Supply.* This dataset contains the portion of vaccines a country has available, relative to their population size. For example, 100% means the country has enough vaccine supply to vaccinate everyone in their country, while 50% means they can vaccinate only half of their residents, and 200% means they have double the number of vaccines needed to fully vaccinate their residents.
3) *Trade Relationships.* This dataset contains the portion of exports going from a source country to a partner country, along with the portion of imports coming from the source country to the partner country. We included both versions to capture unbalanced relationships, for example, if a small Caribbean nation imports nearly all of their goods from the United States, yet this only represents a small portion of the United States' overall exports.
4) *County Distances.* This dataset contains the distance between all countries in pairs. Countries are listed twice, with each member of the pair being both the source and the partner country.

<u>Data Cleaning</u>

After selecting our data sources, we performed data cleaning on all datasets so they could be used in model. We performed the following steps to prepare the data:

1) *Aligning country names to the Internal Standard of Organization's 3-letter country codes*. Originally, each dataset used a different format to identify country names. By merging the datasets using the 3-letter classification, we could access information across datasets.
2) *Filling null values.* Although during our data exploration, we sought datasets covering as much of the world as possible, we were still left with gaps for certain countries in certain datasets. In order to address this problem, we filled the missing data assuming the worst-case scenario. For example, if a country was missing from the vaccine count dataset, we assumed they had no vaccines. And

if a pair of countries was missing from the trade dataset, we assumed they had no trade. By assuming the worst, we ensure that our recommended solution will work, even if the amount of vaccines or the level of trade is higher than we anticipate. Countries missing population data were removed from the dataset, as it is not possible to guess the worst-case population amount.

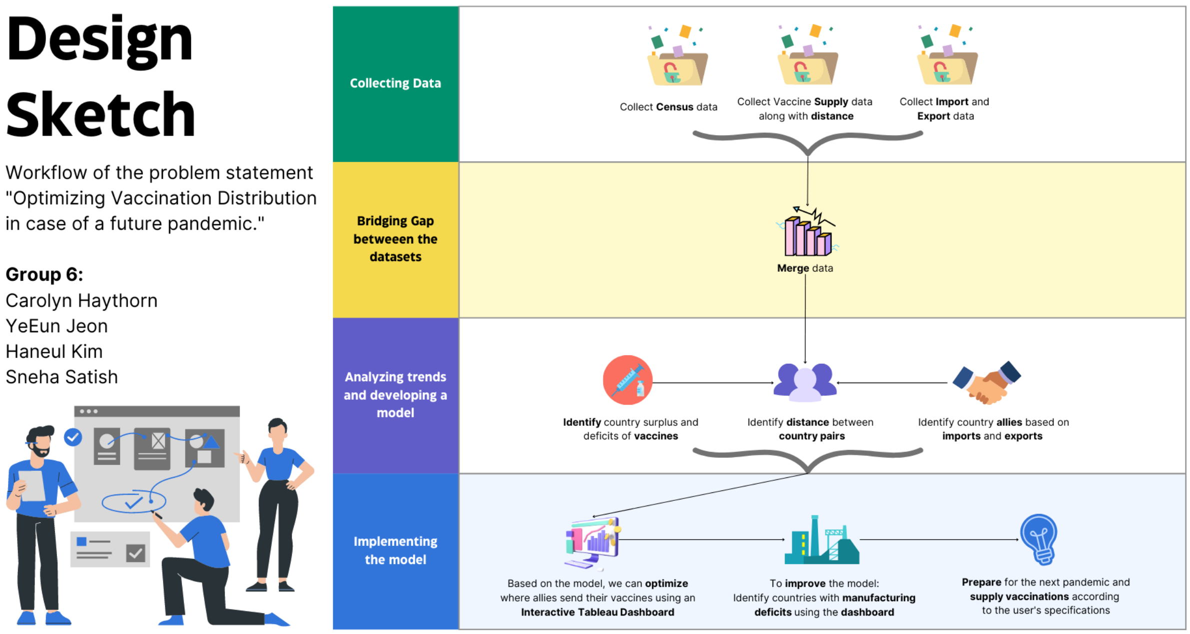
3) *Calculate the vaccine deficit or surplus.* To do this, we took the expected vaccine amount times the country population, and then subtracted the country population. Positive numbers indicate surplus vaccines, while negative numbers indicate vaccine deficits.
4) *Develop the trade indicator.* For each country pair, we summed the values of the exports from the source country and the imports to the partner country. This means the trade indicator becomes a numerical representation of trade only, rather than a specific unit of measure.
5) *Develop the Country Pair Scores.* First, we normalized the trade indicators and distances so both datasets utilized the same unit of measure. Then we assigned ranks to the trade and the distance data, where higher values are better. For the trade data, we kept a normal ranking system, because higher trade is better. For the distance data, we reversed the ranking, because it is better to be closer to a country. We then summed the trade ranking with the distance ranking to get the overall country pair score. Countries which are closer together and share a lot of trade between each other will score the highest.

Proposed Solution

Our Workflow for the project includes the following steps:

1) **Collection of data:** We collected Census, Vaccine Supply, Distance and Trade data
2) **Bridging the gap:** Found the common column in datasets and merged the data. We then cleaned and preprocessed the data. After this, we identified the variables that needed to be analyzed.
3) **Analyzing trends and developing an algorithm:** We identified the countries with surplus and deficits in vaccines. Then identified distance between countries and found out the country allies based on the trade data.
4) **Implementing and visualizing the algorithm:** We optimized where allies could send vaccines using an Interactive Tableau Dashboard.

We present these steps in the design sketch below.



<u>Developing a model</u>

Utilizing the datasets we describe above, our group created an algorithm which accelerates vaccine distribution by assigning supplier – receiver country pairs according to an optimal country score.

The solution utilizes a greedy algorithm of $O(n^2)$. The algorithm utilizes the following steps:

1) **Divide all countries into those with vaccine surplus and vaccine deficits.** Countries with vaccine surpluses are countries which are expected to have more vaccines than needed to serve their own populations. Conversely, countries with vaccine deficits do not have sufficient vaccine supply to fully serve their countries.
2) **For each county with a vaccine deficit, identify viable supply partners.** A viable supply partner must have sufficient vaccine supply to *fully meet the vaccine needs* of the partner country. This simplifies the global vaccine trade by pairing partner countries with *only one* vaccine supplier. However, a surplus country may provide multiple countries with vaccines if the surplus country has sufficient surplus to meet the needs of multiple countries with vaccine deficits.
3) **Of all the viable supply partners, identify the county pair with the highest score.** The country pair score is determined based on the counties' proximity and level of trade shared between each other. We describe this in further detail in the data cleaning section . The supply partner resulting in the highest country pair score for the given deficit country will be selected. The algorithm stores the ideal

pair and the number of vaccines needed to fill the vaccine deficit.

4) **Remove the vaccines provided to the partner country from the supply country's vaccine stock.** Vaccines can only be given to another country once. By removing the supplied vaccines from the supply country's stock, the supply country can continue to be matched with other countries until the surplus is fully used.
5) **Shuffle the supplier data.** In testing the model, we observed that if there was a tie in the country pair score, the supplier coming last alphabetically would be selected, due to the organization of the supplier dataset. By shuffling the supplier data, we ensure more equitable vaccine distribution, so the countries ending in Z are not overburdened with supplier their partner countries.
6) **Iterate through the countries with vaccine deficits until all needs are met.**

Data Analysis

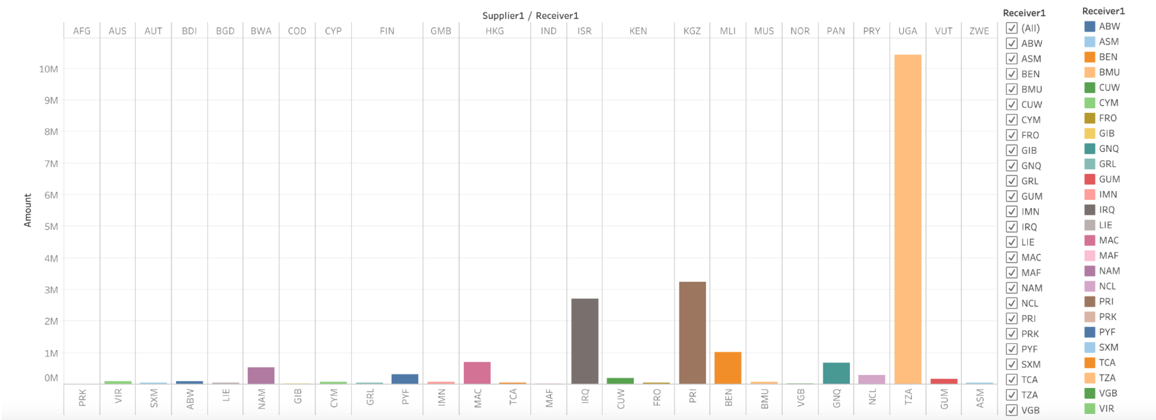
On the right, you can see the country pairs which resulted from our model. Because our dataset utilized data from the end of the COVID-19 pandemic, we only saw a deficit of about 21 million vaccines globally, with smaller island countries being the majority of the countries with vaccine deficits.The results of the algorithm were also visualized with the help of an interactive Tableau dashboard, which you can see below. In the first page, the bar chart shows the ideal country pairs. The countries on top are the suppliers and the bottom are receivers. Users can choose on the right panel which receivers they want to view. Note, the supplier countries here are the ones with surplus vaccines which they can send to the receiver countries who are in deficit of vaccines.

Vaccine Supply: Ideal Country Pairs

Supplier Country	Receiver Country	Number of Vaccines
Afghanistan	North Korea	2
Australia	United States Virgin Islands	99,465
Austria	Sint Maarten	44,175
Bangladesh	Liechtenstein	39,327
Botswana	Namibia	526,672
Burundi	Aruba	106,445
Cyprus	Cayman Islands	68,706
Democratic Republic of the Congo	Gibraltar	32,649
Finland	French Polynesia	306,279
Finland	Greenland	56,466
Gambia	Isle of Man	84,519
Hong Kong	Macau	695,168
Hong Kong	Turks and Caicos Islands	45,703
India	Collectivity of Saint Martin	31,791
Israel	Iraq	2,699,689
Kenya	Curaçao	191,163
Kenya	Faroe Islands	53,090
Kyrgyzstan	Puerto Rico	3,252,407
Mali	Benin	1,004,660
Mauritius	Bermuda	64,184
Norway	British Virgin Islands	31,305
Panama	Equatorial Guinea	681,440
Paraguay	New Caledonia	289,950
Uganda	Tanzania	10,436,970
Vanuatu	Guam	171,774
Zimbabwe	American Samoa	44,273
Total		**21,058,272**

OPTIMIZING VACCINE DISTRIBUTION IN CASE OF A FUTURE PANDEMIC

IDEAL COUNTRY PAIRS



The next visualization in the dashboard provides more information about how the countries were paired together. This is a heat map of the normalized trade indicators between all country pairs. The columns are the receiver country codes and the rows are the supplier country codes. Darker green indicates a higher level of trade between the country pairs. Canada and the USA have the highest trade score, at .937, followed by India and Nepal at .862

TRADE SCORES

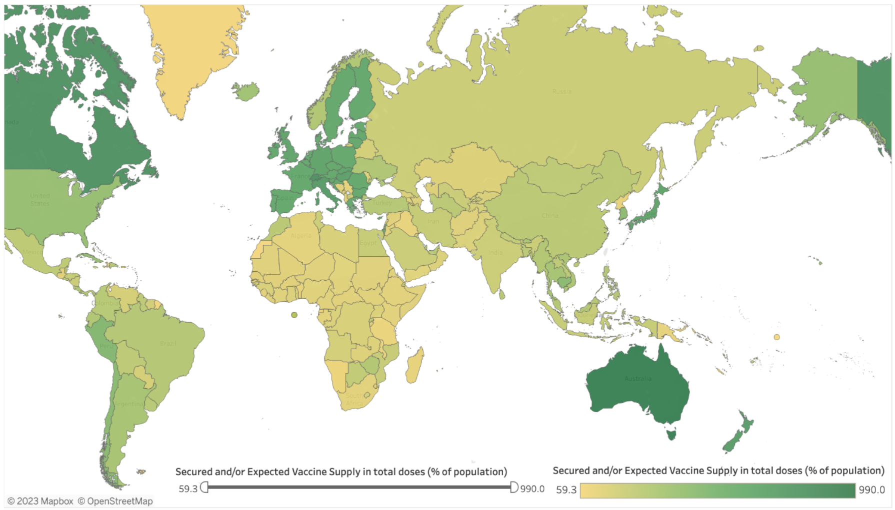
Reporteriso	AFG	AGO	ALB	ARE	ARG	ARM	ATG	AUS	AUT	AZE	BDI	BEL	BEN	BFA	BGD	BGR	BHR	BHS	BIH	BLR	BLZ	BOL	BRA
AFG		-0.381	-0.218	-0.070	-0.767	-0.114	-0.616	-0.568	-0.229	-0.082	-0.297	-0.271	-0.373	-0.376	-0.118	-0.203	-0.100	-0.627	-0.222	-0.186	-0.693	-0.764	-0.675
AGO	-0.381		-0.282	-0.257	-0.385	-0.317	-0.434	-0.665	-0.318	-0.333	-0.094	-0.262	-0.103	-0.144	-0.457	-0.290	-0.281	-0.526	-0.295	-0.352	-0.580	-0.426	-0.287
ALB	-0.218	-0.282		-0.184	-0.581	-0.104	-0.403	-0.783	-0.029	-0.125	-0.254	-0.071	-0.212	-0.193	-0.335	0.000	-0.164	-0.439	-0.007	-0.075	-0.513	-0.552	-0.465
ARE	0.225	-0.241	-0.184		-0.674	-0.071	-0.572	-0.585	-0.203	-0.090	0.238	-0.241	0.175	-0.301	-0.171	-0.171	0.196	-0.624	-0.193	-0.197	-0.693	-0.623	-0.579
ARG	-0.767	-0.391	-0.583	-0.677		-0.673	-0.290	-0.584	-0.589	-0.694	-0.481	-0.560	-0.395	-0.399	-0.841	-0.599	-0.665	-0.348	-0.586	-0.642	-0.331	0.061	0.150
ARM	-0.114	-0.317	-0.103	-0.091	-0.671		-0.507	-0.680	-0.115	-0.023	-0.255	-0.154	-0.280	-0.274	-0.229	-0.082	-0.083	-0.531	-0.109	-0.085	-0.603	-0.653	-0.557
AUS	-0.569	-0.666	-0.782	-0.590	-0.575	-0.680	-0.820		-0.783	-0.657	-0.620	-0.821	-0.769	-0.809	-0.427	-0.767	-0.613	-0.775	-0.788	-0.758	-0.693	-0.649	-0.699
AUT	-0.228	-0.319	-0.029	-0.212	-0.592	-0.116	-0.388	-0.797		-0.131	-0.289	-0.023	-0.241	-0.216	-0.322	-0.020	-0.190	-0.412	0.070	-0.048	-0.485	-0.549	-0.474
AZE	-0.091	-0.333	-0.126	-0.087	-0.689	-0.023	-0.527	-0.657	-0.131		-0.266	-0.178	-0.301	-0.296	-0.209	-0.109	-0.079	-0.548	-0.130	-0.095	-0.618	-0.676	-0.572
BEL	-0.271	-0.311	-0.078	-0.246	-0.564	-0.155	-0.338	-0.834	-0.023	-0.183	-0.313		-0.244	-0.216	-0.375	-0.050	-0.230	-0.366	-0.063	-0.074	-0.438	-0.513	-0.439
BGD	-0.119	-0.457	-0.337	-0.157	-0.814	-0.233	-0.730	-0.437	-0.345	-0.210	-0.364	-0.380	-0.439	-0.476		-0.319	-0.196	-0.724	-0.341	-0.301	-0.727	-0.875	-0.747
BGR	-0.203	-0.292	0.001	-0.174	-0.597	-0.089	-0.418	-0.767	-0.005	-0.111	-0.259	-0.062	-0.226	-0.208	-0.321		-0.151	-0.449	-0.017	-0.061	-0.522	-0.568	-0.484
BHR	-0.100	-0.281	-0.164	0.040	-0.666	-0.083	-0.560	-0.560	-0.190	-0.079	-0.201	-0.235	-0.277	-0.283	-0.199	-0.154		-0.604	-0.175	-0.181	-0.637	-0.675	-0.527
BIH	-0.222	-0.295	-0.005	-0.194	-0.584	-0.109	-0.398	-0.790	0.023	-0.131	-0.269	-0.054	-0.222	-0.201	-0.337	-0.008	-0.175	-0.428		-0.063	-0.502	-0.551	-0.462
BLR	-0.194	-0.356	-0.075	-0.198	-0.637	-0.088	-0.423	-0.758	-0.044	-0.111	-0.319	-0.075	-0.287	-0.265	-0.307	-0.062	-0.181	-0.436	-0.064		-0.505	-0.596	-0.525
BOL	-0.764	-0.426	-0.552	-0.692	0.077	-0.653	-0.203	-0.650	-0.549	-0.676	-0.520	-0.506	-0.400	-0.391	-0.874	-0.567	-0.665	-0.255	-0.551	-0.596	-0.240		0.115
BRA	-0.675	-0.324	-0.471	-0.590	0.065	-0.569	-0.199	-0.699	-0.467	-0.591	-0.428	-0.436	-0.306	-0.300	-0.778	-0.486	-0.572	-0.276	-0.473	-0.501	-0.290	0.056	
BRN	-0.288	-0.571	-0.505	-0.292	-0.831	-0.401	-0.879	-0.223	-0.513	-0.379	-0.480	-0.549	-0.621	-0.640	-0.168	-0.490	-0.362	-0.824	-0.509	-0.472	-0.824	-0.925	-0.892
BWA	-0.402	-0.111	-0.370	-0.264	-0.401	-0.375	-0.531	-0.552	-0.409	-0.384	-0.121	-0.345	-0.215	-0.256	-0.441	-0.376	-0.314	-0.622	-0.385	-0.439	-0.665	-0.464	-0.385
CAN	-0.520	-0.533	-0.360	-0.536	-0.441	-0.437	-0.169	-0.797	-0.314	-0.435	-0.572	-0.264	-0.431	-0.390	-0.575	-0.365	-0.517	-0.108	-0.347	-0.341	-0.163	-0.327	-0.331
CHE	-0.261	-0.313	-0.048	-0.166	-0.543	-0.148	-0.354	-0.821	0.061	-0.160	-0.300	0.004	-0.226	0.632	-0.354	-0.052	-0.217	-0.382	-0.024	-0.079	-0.455	-0.516	-0.433
CHL	-0.820	-0.416	-0.623	-0.734	0.080	-0.719	-0.286	-0.561	-0.621	-0.741	-0.538	-0.589	-0.446	-0.446	-0.892	-0.638	-0.721	-0.329	-0.624	-0.674	-0.299	-0.055	-0.024
CHN	-0.180	0.067	-0.357	-0.201	-0.859	0.024	-0.686	0.070	-0.330	-0.236	-0.455	-0.372	-0.527	-0.553	-0.134	-0.328	-0.298	-0.575	-0.372	-0.291	-0.658	-0.851	-0.454
CIV	-0.409	-0.134	-0.229	-0.324	-0.356	-0.310	-0.304	-0.794	-0.250	-0.331	-0.200	-0.232	-0.035	-0.032	-0.513	-0.244	-0.315	-0.395	-0.237	-0.296	-0.456	-0.360	-0.259
CMR	-0.343	-0.062	-0.213	-0.243	-0.414	-0.262	-0.407	-0.724	-0.246	-0.280	-0.107	-0.228	-0.047	-0.087	-0.436	-0.223	-0.243	-0.487	-0.226	-0.286	-0.550	-0.440	-0.326

Score
-0.997 0.937

Score
-0.997 0.937

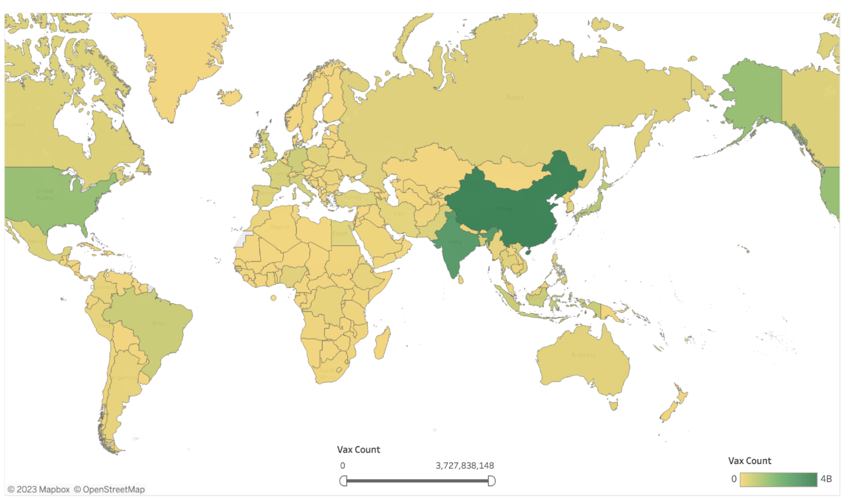
The next chart shows the total portion of vaccines the country has available, with the darker green indicating that the country has enough vaccine supply to vaccinate everyone. The slider at the bottom of the chart can be used to filter out countries by specifying a range. Australia has the highest expected vaccine supply relative to its population at nearly 10x the amount necessary.

EXPECTED/SECURED VACCINE SUPPLY IN TOTAL DOSES

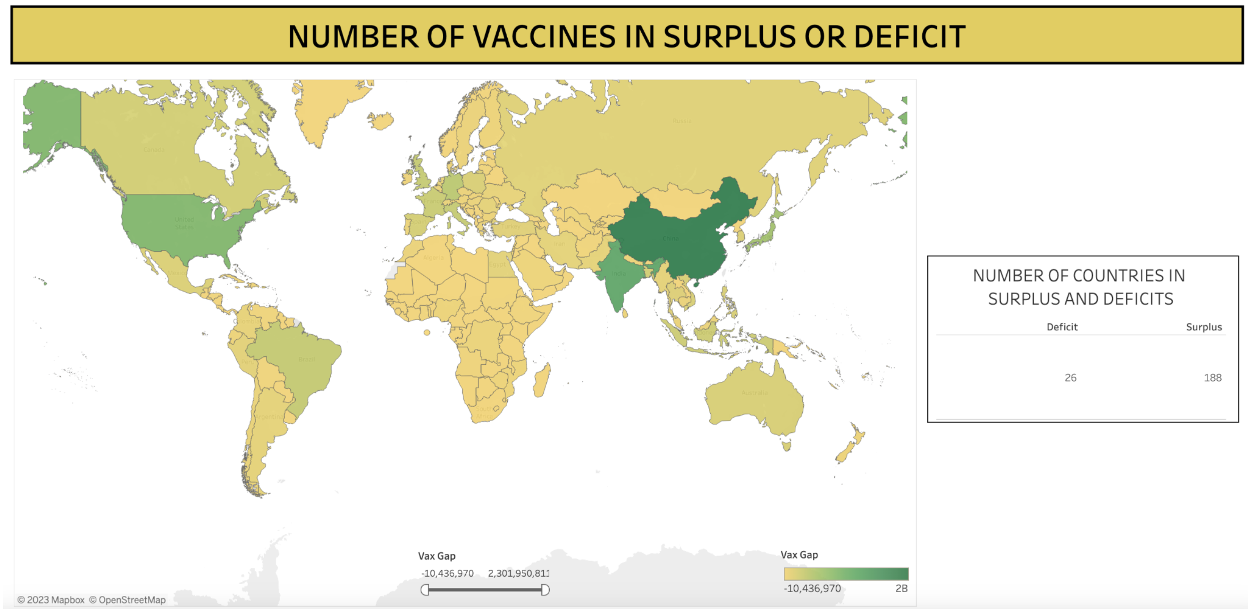


The next heat map shows the total number of vaccines the country has, with the darker green indicating that the country has a higher number of vaccines. The slider at the bottom of the chart can be used to filter out countries by specifying a range. By comparing the chart to the one above, we can see the important difference between expected vaccine supply relative to country population, versus total supply. Although in the above chart, Australia has the highest number of vaccines relative to its population size, we can see below that China and India have the highest total number of vaccines, while Australia is on the lower end of the distribution.

TOTAL VACCINE COUNT



The final heat map shows the number of vaccines by which the country is in surplus or deficit. The slider at the bottom of the chart can be used to filter out countries by specifying a range. The chart on the right shows the total number of countries that are in surplus and deficit. There are 188 countries with surplus vaccines and 26 in deficit. China, India, and the United States have the largest vaccine surpluses, while Tanzania and Iraq have the highest deficits. The data used in this chart is what gives us the foundation for our algorithm.



Areas of Future Study

There are several areas of possible development for our current algorithm. First, the algorithm currently requires sufficient vaccines to fully vaccinate the global population in order to run properly. Although this was suitable for the datasets upon which we built the model, which were collected towards the end of the COVID-19 pandemic when vaccine supply was no longer a major issue, in the case of a future pandemic, it is likely that we will be operating under a global vaccine deficit once again. In order to make the algorithm more applicable to that situation,we recommend that the algorithm include “triage”-like measures, to target first 100%, then 70%, then 30% of a country’s population, depending on vaccine availability. If not even 30% of the population can be covered, the algorithm could then target countries with vaccine deficits and large numbers of “at-risk” criteria such as population density, population age, alcohol use, tobacco use, and average Body Weight Index. These could be aligned to the recommendations set forth by the World Health Organization.

Another area of future study includes transitioning from a greedy algorithm to a weighted graph model. This would allow for the algorithm to more easily recommend two supply countries for one country with a vaccine deficit, which would result in a lower number of wasted vaccines, as countries could share their surplus even if they can't completely fulfill another country's vaccine deficit.

Next, it would be interesting to utilize the vaccine manufacturing data we describe in the exploratory data analysis section in order to predict vaccine supply. Although our group decided that there were too many gaps in the vaccine manufacturing dataset for it to be a viable source for this project, future work could include further exploration of this dataset, or even the development of better mechanisms to capture similar information in-real time at a global scale.

Finally, additional complexity could be added to the country-pair score. Although we only utilized trade and proximity in our model, additional factors such as linguistic and cultural similarities, desired vaccine type, and number of shared political agreements between the countries could be included in future development.

Conclusion

The COVID-19 pandemic starkly demonstrated the interconnectivity – and fragility – of our global supply chain. As the experience of lockdown, supply chain shortages, and desperation for a vaccine becomes a memory from "COVID times" for many, it is important to take stock of what caused the pandemic to be experienced so harshly across the globe. The evidence is clear that failure to effectively and equitably distribute the COVID-19 vaccine resulted in new variants which both prolonged the pandemic and ultimately cost lives. However, we know that vaccine distribution is not a simple task. Nationalism, economic competition, political alliances, and practical trade challenges can make it difficult to think equitably and develop a rational vaccine distribution plan which allows for the quickest possible reduction of life-threatening risk from future diseases. By utilizing an algorithm such as the one which our group developed, the decision of *where* vaccines should be sent and *by whom* is made simpler, and efforts can instead be spent on producing and delivering vaccines to those who need it the most. International organization such as the World Trade Organization, the United Nations, and the World Health Organization should partner together now to develop and maintain strong mechanism to track factors which which used in our algorithm such as vaccine production and supply and country overall and at-risk population in order to be ready to implement the vaccine sharing algorithm when the next pandemic arrives.

References

[1] Fonseca, L. M., & Azevedo, A. L. (2020). COVID-19: outcomes for global supply chains. Management & Marketing. Challenges for the Knowledge Society, 15(s1),

424-438.
[2] Matrajt, L., Eaton, J., Leung, T., & Brown, E. R. (2021). Vaccine optimization for COVID-19: Who to vaccinate first?. Science Advances, 7(6), eabf1374.
[3] McIntyre, P. B., Aggarwal, R., Jani, I., Jawad, J., Kochhar, S., MacDonald, N., ... & Cravioto, A. (2022). COVID-19 vaccine strategies must focus on severe disease and global equity. The Lancet, 399(10322), 406-410.
[4] Petersen, E., Ntoumi, F., Hui, D. S., Abubakar, A., Kramer, L. D., Obiero, C., ... & Zumla, A. (2022). Emergence of new SARS-CoV-2 Variant of Concern Omicron (B. 1.1. 529)-highlights Africa's research capabilities, but exposes major knowledge gaps, inequities of vaccine distribution, inadequacies in global COVID-19 response and control efforts. International Journal of Infectious Diseases, 114, 268-272.
[5] Ye, Y., Zhang, Q., Wei, X., Cao, Z., Yuan, H. Y., & Zeng, D. D. (2022). Equitable access to COVID-19 vaccines makes a life-saving difference to all countries. Nature human behaviour, 6(2), 207-216.
[6] Valizadeh, J., Boloukifar, S., Soltani, S., Hookerd, E. J., Fouladi, F., Rushchtc, A. A., ... & Shen, J. (2023). Designing an optimization model for the vaccine supply chain during the COVID-19 pandemic. Expert Systems with Applications, 214, 119009.
[7] Habibi, F., Abbasi, A., & Chakrabortty, R. K. (2023). Designing an efficient vaccine supply chain network using a two-phase optimization approach: a case study of COVID-19 vaccine. International Journal of Systems Science: Operations & Logistics, 10(1), 2121623.
[8] Zheng, Y. J., Chen, X., Song, Q., Yang, J., & Wang, L. (2022). Evolutionary optimization of COVID-19 vaccine distribution with evolutionary demands. IEEE Transactions on Evolutionary Computation.
[9] Three priorities to urgently increase access to COVID-19 vaccines - IFPMA
[10] What you need to know about newly authorized COVID-19 antiviral treatments (phrma.org)