Vaccine Distribution Optimization:
Preparing for the Next Pandemic
DSKUS Group 6

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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.

According to the World Health Organization (WHO), the COVID-19 public health emergency lasted 1,191 days, and even in May 2023, the risk of new variants emerging remains a global health threat.[1] Since a large range of activities and parties are involved in the global supply chain, fast recovery from future pandemics is necessary to mitigate disruptions in the global supply chain. Equitable vaccine distribution will be a critical factor in ensuring future pandemics are eradicated with the lowest possible loss-of-life [3].

Unequal vaccine distribution undoubtably prolonged the COVID-19 pandemic. The explosive global spread of COVID-19 pandemic generated international consensus in principle, between the 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" [4]. 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."[2] "Tragically, concerns regarding access to COVID-19 vaccines in Africa are similar to those raised during the HIV pandemic in

[1]Lenharo, "WHO declared end to COVID-19's emergency phase" *Nature,* 05 May, 2023. Accessed online.
[2]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.

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 (Nachega et al., 2021a) - a disparity that resulted in many preventable deaths in these high-burden settings" [3].

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 [4].

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. To do so, equal vaccine distribution is needed.

Literature Review

Much research has been carried out in the field of vaccine distribution optimization problems and there were various views 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 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-arts and, hence, contribute to accelerating the achievement of herd immunity.

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). This work was conducted in four parts.

Korean Export and Vaccination Rates

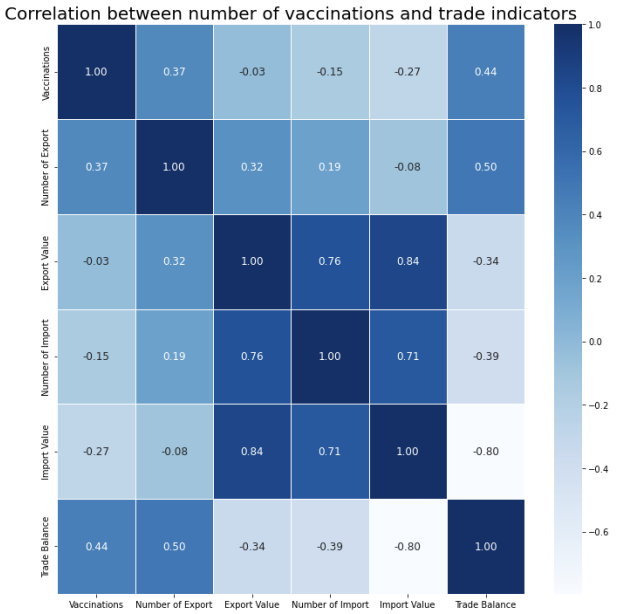
Using the Trade Statistics published by the Korean Customs Service, we compiled a dataset of the top 20 trade surplus items each month, from January 2020 - December 2022. For the time period examined, electronic integrated circuits, cars, and petroleum oil had the largest overall trade surplus (called 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.

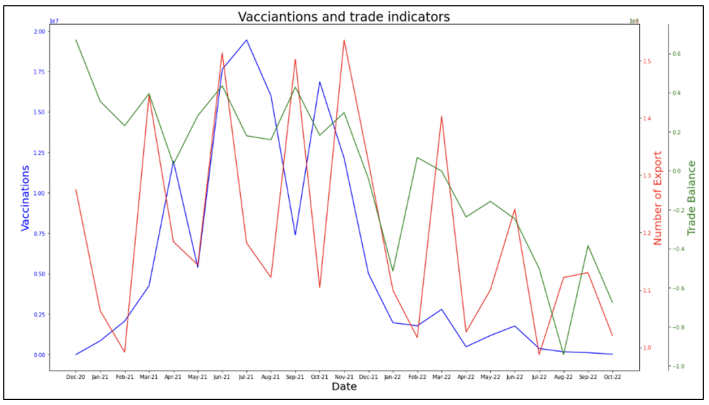
Positive Trade Balance: Top 10 Items

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 the 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.

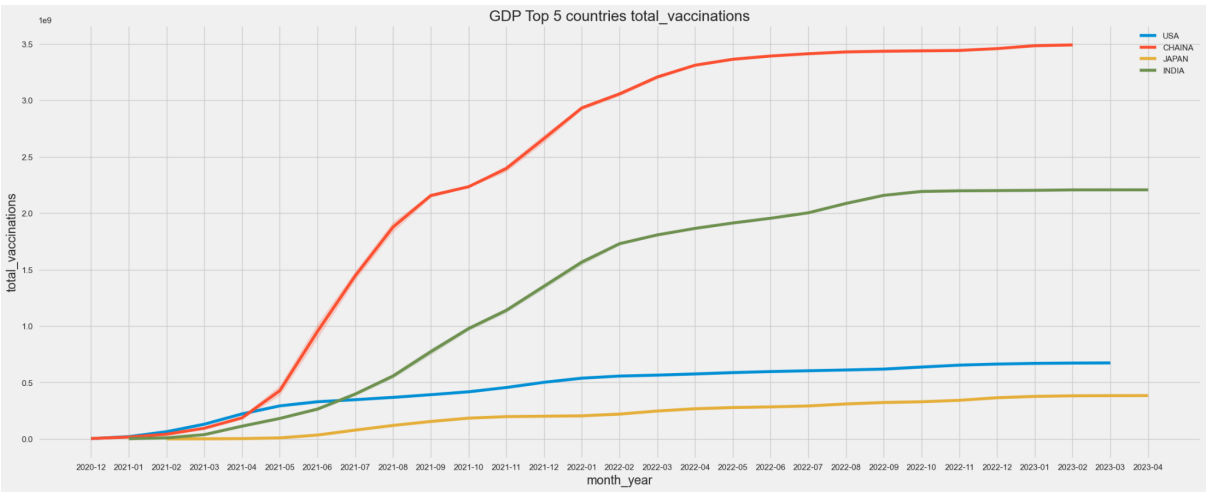


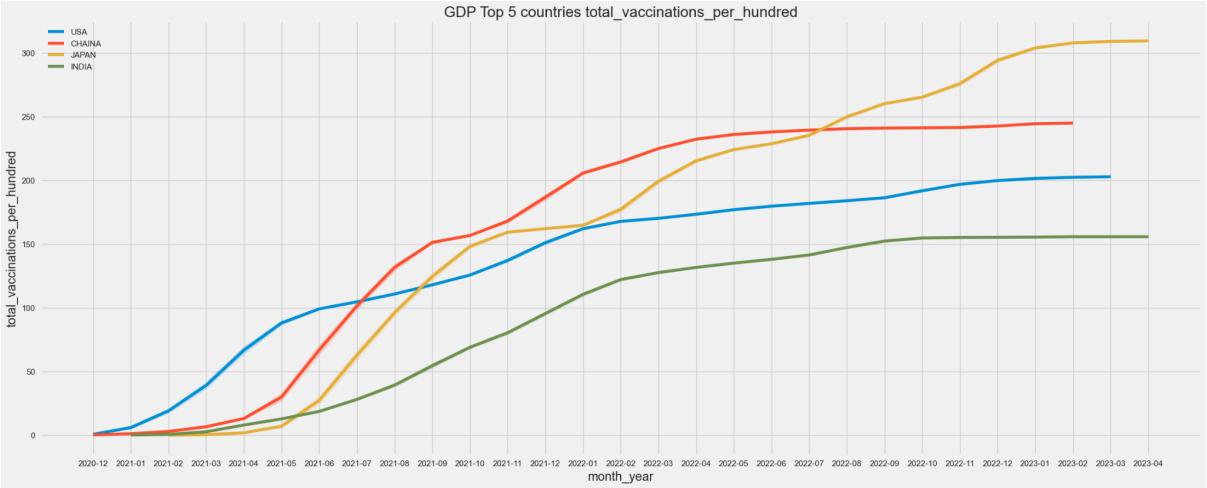


By plotting the line graph, in 2021, as the number of vaccinations increased, the number of exports also tended to increase, and in 2022, as the number of vaccinations decreased, exports and trade balance also decreased. Therefore, these results show that the number of vaccinations is related to exports.

<u>Relationship between Vaccination Rates and Gross Domestic Product</u>

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.

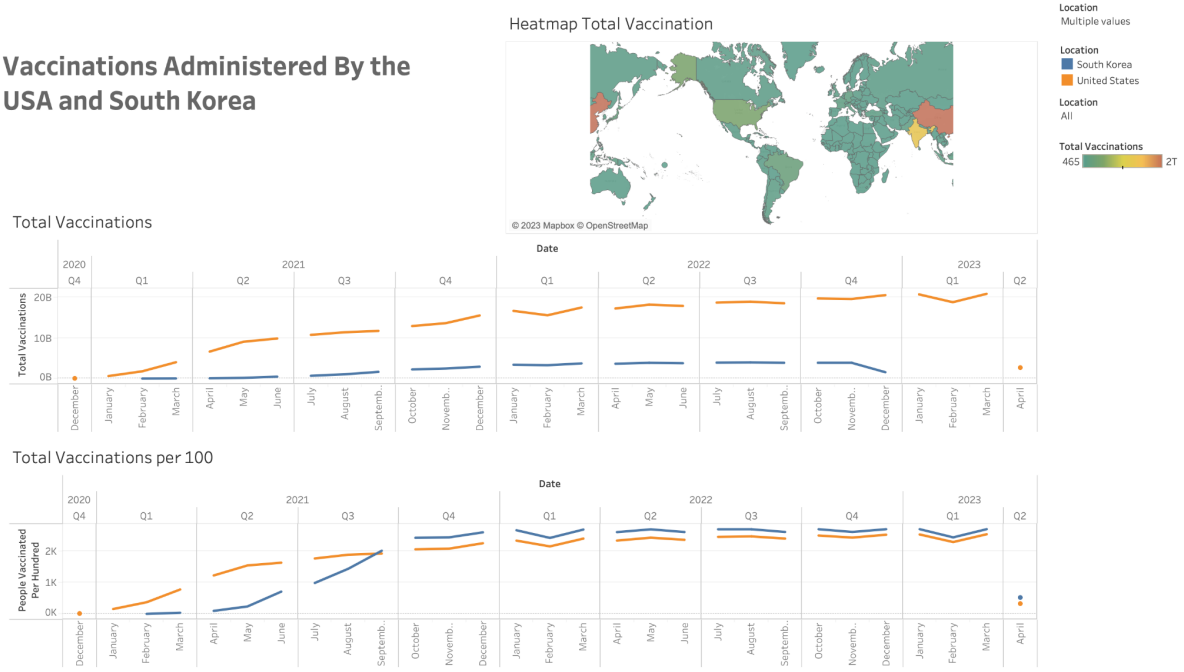




The countries with the lowest GDP are Estonia, Nepal, Paraguay, Bahrain, and Bolivia. Of those countries, Nepal had the most vaccines, followed by Bolivia, Paraguay, Bahrain,and Estonia.

Comparison of USA and Korea Vaccination Rates

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.

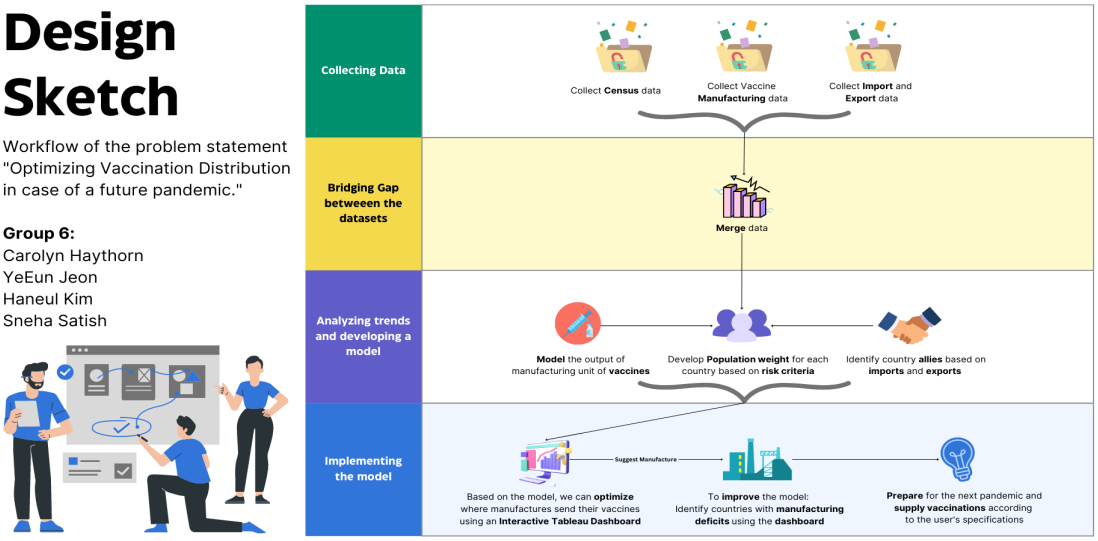


The geospatial heat map and top temporal visualization show the total vaccinations received in South Korea (blue) and United States (Orange) from December 2020 to April 2023. With the Geospatial heat map, where the darker color represents a higher number of vaccinations administered and the lighter represents 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.

Design Sketch and Project Workflow

Our project proposal is to model optimal vaccine distribution based on available manufacturing plants. The focus is to determine what portion of manufactured vaccines should be shared between HIC and LMIC countries, in order to minimize the spread of illnesses such as COVID-19. In addition, we plan to suggest ideal locations for future vaccines manufacturing plants to increase the speed and reduce the cost of vaccine distribution.



The workflow consists of four steps:

1. Collecting the data: We will be using the census, manufacturing and import/export data.
2. Bridging the gap: Finding the common column in datasets and merging the data. We will then clean and preprocess the data. After this, we identify the variables that need to be analyzed.
3. Analyzing trends and developing a model: Using data visualization techniques, we will explore the data. We will identify the trends and patterns present, and use this information to inform the model design. We model the output of the manufacturing unit of vaccines, develop population weights and identify country allies and check how many deaths can be minimized in the next pandemic if two countries come together. We will utilize established algorithm techniques to build the model, such as shortest path algorithms.
4. Implementing the model: After training and validating the model, we will test the accuracy and then create an interactive dashboard where we will optimize distribution of vaccines and also identify where there are deficits in manufacturing units. Accordingly, we can prepare for the next pandemic.

Data Sources

The project utilizes three main data sources:

1. *Vaccine Manufacturers:* Compiled by the Geneva Graduate Institute of Global

Health Centre, this dataset contains a list of the current COVID-19 vaccine manufacturers per country, along with the type and amount of vaccines they produce annually. This data source is no longer maintained; so additional data infrastructure will need to be built to "future-proof" this project. It is possible that country governments have access to similar information, for example, in the United States, this information may be collected through the Internal Revenue Service or theDepartment of Agriculture.

2. *Population Data:* Maintained by the World Bank, this dataset contains global sub-national population data. Information is updated when new population counts become available. By focusing on sub-national data, we can fine-tune the model to target heavily populated states/provinces before less populous, rural areas. The World Bank collects additional information which can be used to fine-tune the model, such as the average age of the populations and the percent of the population with risk factors, such as individuals who smoke or drink large amounts of alcohol.
3. *Trade Data:* Maintained by the World Trade Organization, this dataset contains information about the amount of trade shared between two countries. We plan to use this information to fine-tune the model, so countries that already have strong trade connections are more likely to share vaccines with each other.

Project Audience

Our group plans to create a tableau dashboard containing the information about optimized vaccine distribution. We will allow for user input to develop a model that meets the user's needs – for example, they will be able to decide whether or not to account for trade relationships when viewing the data. Ideally, the model will inform both ideal vaccination distribution in the current state, along with ways to improve vaccination distribution through additional manufacturers or increased trade between two countries. This wide application makes it useful for numerous stakeholders, including WHO employees, government officials, and pharmaceutical representatives. In addition, although our project is specifically focused on vaccine distribution, the model could eventually be tweaked to support additional products, for example a multi-national company could utilize the algorithm to assess how to distribute global products.

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