A Data-Driven Approach to Optimize Vaccine Allocation for Fostering Equity and Efficiency

Abstract:

The COVID-19 pandemic has presented significant challenges in the management of the vaccine supply chain, prompting researchers to investigate the difficulties associated with vaccine distribution. In this research, we present the detailed operations of vaccine distribution in the United States and the challenges that officials faced in fairly and efficiently allocating vaccines to each state in its early stages. We then present an analytical methodology to overcome these challenges. We analyze different equity theories as an alternative to the status quo of pro rata policy and present findings in the context of a case study. The results can help officials make fast, fair, and efficient decisions during future pandemics and natural disasters when scarce vaccines and supplies need to be allocated to different regions. In our model, we consider the vulnerability and vaccine hesitancy among the populations of different regions, as well as the limited capacity of vaccine administration in each region.

# Introduction

Despite the abundance of scientific evidence regarding the safety and effectiveness of vaccines, vaccine hesitancy causes individuals to refuse vaccines. This hesitancy is not exclusive to the COVID-19 vaccine but is also prevalent in other infectious diseases (Beleche et al., 2021; Salmon et al., 2015). Given that vaccination plays a crucial role in controlling diseases during a pandemic, the refusal to get vaccinated can hinder the progress in ending an outbreak. Data reveals that vaccine hesitancy was quite prominent at the start of 2021 when the COVID-19 vaccine became available to certain segments of the public. The primary factors mentioned as causes for this hesitancy included worries about potential adverse effects, a preference for a "wait and see" approach due to uncertainties regarding vaccine efficacy, belief in pre-existing immunity, and skepticism regarding the vaccine's origin (Bayati et al., 2022). However, vaccine hesitancy tends to change over time as people gain more information. For instance, the percentage of individuals aged 18 years and older who expressed hesitancy towards receiving the COVID-19 vaccine decreased from 22% to 16% over a 12-week period spanning from January 2021 to the end of March 2021(Beleche et al., 2021).

In the early stages of vaccine distribution, when supplies are severely limited, it is essential to recognize the issue of vaccine hesitancy. Despite vaccines being available for eligible groups in certain regions, a significant proportion of individuals within those regions may be unwilling to receive the vaccine. In these circumstances, a more equitable approach would be to allocate those vaccine doses to regions characterized by high vulnerability and lower levels of hesitancy. By strategically allocating doses in this manner, the impact of the limited vaccine supply can be optimized, which can better help to achieve the herd immunity.

Utilizing social equity in the distribution of vaccine at the early stage of pandemic when there is limited supplies can significantly reduce infection rates (Dastgoshade et al., 2022). It is crucial to evaluate policies using different equity theories because a policy may seem fair from one perspective but unfair from another (Behbahani et al., 2019).

Prior to starting the vaccination process, the CDC has advised states to prepare for three vaccination phases (CDC, 2020). In Phase 1, when the vaccine supply is limited, the main objective should be to prioritize the initial critical population. This includes healthcare and essential workers, as well as individuals at higher risk for severe illness. It is crucial to efficiently manage logistics in order to minimize wastage and inefficiencies. During Phase 2, a larger quantity of vaccines will be available. The focus should shift towards expanding the network of healthcare providers to vaccinate individuals who were not vaccinated in Phase 1, as well as accommodating the new population eligible for vaccination. In Phase 3, there will be an ample supply of vaccine doses for the entire population, with surplus doses available. The main objective in this phase is to ensure fair and equal access to vaccination for the entire population.

An important aspect to consider is that there will be a limited supply of vaccines at the start of the program, but it is expected to increase rapidly during the initial phase of vaccination. Consequently, the planning should be adaptable yet sufficiently detailed to accommodate various potential situations (CDC, 2020).

# Literature review

Most of the research on vaccine distribution primarily addresses preparedness for expected and recurring epidemics, such as seasonal influenza. However, there is a limited amount of literature available that specifically addresses the challenges posed by unpredictable outbreaks, such as a pandemic influenza (Bertsimas et al., 2020; Duijzer et al., 2018). .

## Social equity in vaccine distribution

The strategies in allocating and distributing COVID-19 vaccines has disproportionately affected people of different races, ethnicities, and economic backgrounds (J. T. Chen & Krieger, 2021; Ogedegbe et al., 2020; Vahidy et al., 2020). The inequality in vaccine distribution not only leads to health injustices for individuals and communities, but also hinders the economic recovery process in developing nations (Bayati et al., 2022). Social equity, also known as social justice or fairness, refers to a situation in which the allocation of benefits or costs within a population is perceived as fair and suitable (Litman, 2022). According to the CDC definition, social equity in vaccine distribution refers to the fair and equal access to COVID-19 vaccination for all eligible individuals (CDC, 2022b). Various social, geographic, political, economic, and environmental factors present obstacles to vaccine access and acceptance, which may negatively impact racial and ethnic minority communities.

For instance, a study conducted in the United States (Donadio et al., 2021) has indicated that women have a higher rate of vaccine administration compared to men. In Maryland, (Cardona et al., 2021) discovered through their research that vaccination rates among Black individuals were lower. However, it remains unclear whether the lower vaccination rates among these groups are due to inequitable distribution of vaccines or the population's unwillingness to receive them. Additionally, research indicates that politicians’ racial bias has led to higher vaccination rates among White and Indigenous populations in the region (Agarwal et al., 2021). The political environment is also reported as the one of the factors affecting the vaccine distribution. (Agarwal et al., 2021) study in the United States revealed that the outcome of the 2020 presidential election, along with the prevailing political sentiment, influenced the allocation of the Covid-19 vaccine. For a detailed literature review on the factors contributing to the inequality of Covid-19 vaccine distribution, readers are referred to (Bayati et al., 2022). Ensuring fairness in vaccine allocation is not only an ethical concern but also acknowledges the principle of equal rights for all individuals (Dastgoshade et al., 2022).

Although various efforts have been made to assess equity within transportation and humanitarian logistics (Anaya-Arenas et al., 2018; Gutjahr & Fischer, 2018; Huang & Rafiei, 2018; Yu et al., 2018), the integration of social equity into operations research is still in its early stages (Dastgoshade et al., 2022). In particular, the application of equity measurements in vaccine supply chains requires further development (Behbahani et al., 2019; De Boeck et al., 2020; Enayati & Özaltın, 2020). This is because vaccine supply chains have unique characteristics, such as population vulnerability, storage requirements, vaccine hesitancy, and the need for widespread distribution, which need to be taken into consideration (Balcik et al., 2022; Orgut et al., 2023). The CDC recommends utilizing Social Vulnerability Index (SVI) to evaluate potential negative impact on communities caused by external factors that affect human health (CDC, 2022b).

Researchers have used different approaches to measure social equity in vaccine distribution. (S. I. Chen et al., 2014) conducted a study focusing on the problem of vaccine allocation and inventory management in developing nations with the aim of enhancing the vaccination coverage of children. To ensure fairness, they set specific requirements on the minimum vaccination rate that each facility should achieve during different time periods. In 2019, (Behbahani et al., 2019) proposed a mathematical way to represent different social equity theories and demonstrated their application in designing transportation networks. (Enayati & Özaltın, 2020) proposed a mathematical programming model for fair distribution of influenza vaccines. They divided the population into multiple subgroups and the required vaccines were distributed to each subgroup in an equitable manner to prevent epidemic outbreaks. In order to promoting equity among subgroups, e.g., geographic regions and age groups, the authors utilized the Gini coefficient as an upper bounded constraint in their influenza vaccines allocation epidemic model.

The Gini coefficient is a commonly used economic concept and is widely recognized as one of the most popular measures of equity in social welfare literature (Marsh & Schilling, 1994). It was initially introduced by (Gini, 1997) to tackle income inequality. The coefficient ranges from zero, indicating perfect equity where everyone has the same income, to one, indicating perfect inequity where one person receives all the income. A significant limitation of the Gini coefficient is its failure to account for the susceptibility of various subgroups to diseases (Enayati & Özaltın, 2020).

(Bertsimas et al., 2020) introduced an approach that combines predictive and prescriptive techniques to allocate vaccines during the COVID-19 pandemic, utilizing U.S. data. Their objective was to enhance fairness in vaccine distribution by allocating vaccines to a proportion of the eligible susceptible population. In an extension work, (Bertsimas et al., 2022) addressed the issue of determining the optimal locations for COVID-19 vaccination centers in the United States and how to distribute vaccines to these sites. Their focus was on ensuring fairness in the process. They aimed to achieve fairness by: (i) ensuring that the proportion of vaccination sites in each state reflects its population size (II) distributing vaccines across sites in a manner similar to a uniform distribution, and (III) avoiding a significant deviation in the proportion of vaccines allocated to each state compared to its population share. They used a pro rata policy as a benchmark for their analysis.

(Rastegar et al., 2021) proposed a mixed-integer linear programming model for location allocation problem of vaccine distribution in developing countries. They used pro rata policy in the objective function by maximizing the minimum fill rate, i.e., the number of vaccines allocated per demand, to ensure fair distribution. Additionally, their model considers the minimization of transportation costs to enhance the efficiency of the distribution process. (Tavana et al., 2021) extended (Rastegar et al., 2021) model by accounting for budget limitations, management of the cold supply chain, prioritization of individuals in the community, and vaccine order lead time.

In 2022, (Dastgoshade et al., 2022) expanded on (Behbahani et al., 2019) work by using the social equity theories to address the problem of COVID-19 vaccine network distribution design. (Dastgoshade et al., 2022) addressed the social equity in COVID-19 vaccine distribution by utilizing three social justice theories including Rawls, social welfare (or utilitarianism), and Sadr. The Gini index is utilized to mathematically represent Sadr’s theory. They concluded that using the Rawls' theory leads to a higher percentage of vaccine coverage in rural areas. On the other hand, utilitarianism ensures a greater distribution of vaccine doses among social groups compared to both the Sadr and Rawls theories. Overall, Sadr's theory performs better than Rawls' theory in terms of both allocation and cost considerations. (Munguía-López & Ponce-Ortega, 2021) presented a different formulation for Rawls theory by maximizing the lower bound for vaccine allocation. They also incorporated social welfare and Nash theories to assess the level of social equity in vaccine distribution. In contrast to the findings of (Dastgoshade et al., 2022), they concluded that the social welfare approach tends to prioritize regions with larger populations. (Anahideh et al., 2022) proposed a mathematical model to create a vaccine distribution plan that ensures fairness in terms of geography and socioeconomic factors.

(Balcik et al., 2022) created an integer programming model to distribute limited vaccines fairly and efficiently among subgroups, such as counties. The researchers assessed fairness by quantifying the deviation from predetermined equitable coverage levels for regions and priority groups. Equitable coverage was determined using a weighted pro-rata allocation policy, where the significance of locations and priority groups captured through weights defined by decision makers.

(Fadaki et al., 2022) suggested using demographic information to assess the vulnerability of different subgroups and categorize individuals into priority groups. In their mathematical model, they aimed to achieve a fair allocation by minimizing the weighted risk of unvaccinated populations. These weights are calculated based on susceptibility and exposure rates, ensuring a more equitable distribution of vaccines. (Orgut et al., 2023) conducted a study aiming to improve time-based equity by reducing the maximum travel time for individuals traveling between regions for vaccination purposes.

## Efficiency and effectiveness in vaccine distribution

Efficiency and effectiveness are two important factors when it comes to vaccine allocation and distribution during pandemics. Efficiency is commonly understood as the act of minimizing costs and maximizing the utilization of resources, whereas effectiveness is defined as the ability to control the spread of the disease. Several studies attempted to propose efficient and/or effective models for vaccine distribution. For instance, (Yarmand et al., 2014) focused on improving efficiency by minimizing the overall cost of vaccinations by reducing the number of administered vaccine doses, while (Lim et al., 2022) suggested a redesign of the vaccine supply chain network to enhance resource allocation and strategic decision-making, specifically focusing on the economic aspects of vaccine distribution networks.

(Wang et al., 2023) incorporated uncertainty of vaccine supply and emphasized the utilization of drone delivery to reach remote areas. Their model determines the optimal location for a vaccination facility, assess the capacity of the transportation network, and schedule vaccinations. They measure efficiency through minimizing total cost including the initial cost of establishing healthcare facilities, the cost of deploying drones, the cost of accessing vaccinations, and the cost incurred for maintaining inventory. On the other hand, (Enayati & Özaltın, 2020) and (Orgut et al., 2023) emphasized the importance of effectiveness, defining it in terms of extinguishing outbreaks with minimal vaccine doses and avoiding the allocation of vaccines beyond demand, respectively.

(Balcik et al., 2022) assessed the effectiveness of vaccine distribution by determining the overall average vaccination coverage in the network. However, their model did not consider efficiency and cost factors in the distribution process. (Lusiantoro, 2022) also formulated a mathematical model that utilized the maximal covering location problem to enhance the efficiency COVID-19 vaccine distribution, aiming to maximize the vaccination coverage.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Paper** | **Single-Multi period** | **Single or multiple vaccine type** | **Vaccination capacity** | **Vaccination hesitancy** | **Equity metric** | **Efficiency/Effectiveness**  **metric** | **Method** | **CDC phase (1,2,3)** | **Strategist/ tactical** | **Location** | **Allocation** |
| (Orgut et al., 2023) | Single | Single | Yes | \* | Travel durations | Minimizing the number of unused vaccines and  percentage of unmet demand | Mixed-Integer Linear Programming | 2, 3 | tactical |  | \* |
| (Balcik et al., 2022) | single | Multi | Yes | - | Deviation from pre-determined fair coverage levels | Overall vaccine coverage | Integer programming | 1 | Tactical |  | \* |
| (Enayati & Özaltın, 2020) | Single | Single | - | - | Gini Coefficient | Reducing spread of a disease | SEIR epidemic models | 1 | Operational |  | \* |
| (Dastgoshade et al., 2022) |  |  |  | - | Social welfare, Rawl, and Sadr theories | Cost-based efficiency |  |  | ?? |  |  |
| (Lim et al., 2022) | Single | Single | yes | -- | - | Minimizing transportation, storage, and operating costs | Mixed-integer programming | - | Strategic | \* | - |
| (Yarmand et al., 2014) | Single | Single | - | - | Lower bound on vaccination coverage | Vaccination cost | Two-stage stochastic programming | 1 | Tactical | - | \* |
| (Bertsimas et al., 2020) | Multi | Single | yes | - | ?? | Minimizes the number of deaths | DELPHI epidemiological model | 1 | Tactical | - | \* |
| (Rastegar et al., 2021) | multi | single | yes | - | Maximizing the minimum fill rate | Minimizing transportation costs | Mixed-integer linear programming | - | Strategic, Tactical | \* | \* |
| (Tavana et al., 2021) | Multi | Multi | yes | - | Maximizing the minimum fill rate | Total cost not exceeding budget | Mixed-integer linear programming |  | Strategic, Tactical | \* | \* |
| (Wang et al., 2023) | Multi | Single | No | - | Relative gap between the highest and lowest fill rates. | Total cost | Two-stage robust programming | 1 | Strategic, Tactical | \* | \* |
| (Fadaki et al., 2022) | Multi | Single | Yes | - | The weighted risk of unvaccinated population | Minimizing vaccine transfers between locations. | Mixed integer programming | 3 | operational | - | \* |
| (S. I. Chen et al., 2014) | Multi | Multi | yes | - | Constraint on Vaccination rate | Maximize the number of vaccinated individuals. | Mixed integer programming | 3 | tactical | - | \* |
| (Munguía-López & Ponce-Ortega, 2021) | Single | Single | - | - | Social welfare, Rawl, and Nash theories | - | LP and NLP | 1 | tactical | - | \* |
| (Jarumaneeroj et al., 2022) | Multi | Multi | Yes | - | Lower bound on vaccination coverage | Minimizing total number of infectious individuals | Disease spread model | 2, 3 | Tactical and operational | - | \* |
| (Goodarzian et al., 2022) | Multi | Multi | Yes | - | Minimizing the maximum unmet  demand | Minimizing the total vaccination  Cost and delivery time | MILNP | 2,3 | Strategic, tactical, and operational | \* | \* |
| Current work | Multi | Multi | Yes | \* |  |  |  | 1 | Tactical |  | Allocation |
| Future work |  |  |  |  |  |  |  | 1,2,3 | Tactical and strategic |  | Location, Allocation |

Strategic: Location, network design

Tactical: allocation, inventory management

Operational: Daily Scheduling, Administration

**[Our contribution]:** Incorporate vaccine hesitancy and social vulnerability index in the model and comparing different social equity theories.

# Math Model

|  |  |
| --- | --- |
| **Parameters** |  |
|  | Initial eligible population in county |
|  | The new population that become eligible for vaccination in county during week . |
|  | Hesitancy rate of population in county during week |
| 90 percentiles | Vaccination capacity of vaccine type in county during week |
|  | Available number of vaccines to be allocated in week |
|  | Social vulnerability index for county |
| **Decision Variables** |  |
|  | Allocated vaccine to county during week |
| **Auxiliary variable** |  |
|  | The unvaccinated and eligible population in county during week . |
|  |  |
|  |  |
| **Constraints:** |  |
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|  |  |
|  |  |
|  |  |
|  | is the minimum threshold. See (Ochoa-Barragán et al., 2023) and (Munguía-López & Ponce-Ortega, 2021) for its estimation |
|  |  |

We approached the vaccine allocation problem as a sequential decision-making problem, where officials make allocation decisions on a weekly basis. In each week, denoted as period , if the vaccine allocation to a specific location falls short of the demand, the unmet demand will be rescheduled for the following periods.

Demand in each period , is calculated according to the following equation.

To determine the most effective distribution of vaccines across various counties, different mathematical models are created to account for various social justice theories. These models consider the social vulnerability present in each county.

1. **Pro-rata policy**

The pro-rata vaccine allocation policy is a strategy for distributing the available vaccine doses to various areas in accordance with their respective population sizes. In the United States, the federal government allocated COVID-19 vaccines to the states using a pro-rata formula, based on each state’s adult population as of 2018 (Simunaci, 2020). The following formula is utilized to allocate vaccines based on this pro-rata policy.

1. **Rawl’s policy**

According to the John Rawl’s theory of justice (Rawls, 1971), the distribution of benefits should favor the poorest segment of society. This approach aims to gradually bridge the gap between advantaged and disadvantaged groups within the societal framework (France-Mensah et al., 2019).

Dastgoshadeh et al, divided the population into different social groups. But, we used vulnerability index instead of dividing to different groups.

1. **Social welfare (utilitarianism) policy**

The core principle of this theory is to maximize the overall benefits experienced by every individual within the population. This theory emphasis that society benefits the most as a whole, without necessarily identifying which specific groups receive the greatest benefits (Behbahani et al., 2019; France-Mensah et al., 2019).

1. **Gini Index**

A picture containing text, font, screenshot, information

Description automatically generated

1. **Gini Index**

A black text on a white background

Description automatically generated with medium confidence

# Data

* **Vaccine distribution and administration**: The data about the distribution and administration of vaccines for each state and jurisdiction is obtained from (CDC, 2022a).
* **Vaccine hesitancy**: The vaccine hesitancy rate at the county level is obtained from the publicly available data (*Vaccine Hesitancy for COVID-19: State, County, and Local Estimates | ASPE*, 2021). We assume that the vaccine hesitancy rate for each county decreases by 0.005 per week.
* **Vaccination capacity**: To determine the vaccination capacity at the county level, we utilized the methodology proposed by (Orgut et al., 2023). Specifically, we estimated the vaccination capacity for each county as the 90th percentile of the number of vaccines administered during the first 15 weeks of 2021. The data on administered vaccines at the county level is accessible at (CDC, 2023)

Since data regarding the vaccination capacity for each state is not available, we assume that the weekly vaccination capacity for each specific vaccine type within each state is equal to the number of administered vaccines of that specific type (CDC, 2022a).

* **Vaccine supply**: To determine the weekly supply of each vaccine type, we assume it is equal to the combined quantity of those vaccine types distributed among different jurisdictions in the United States (CDC, 2022a).
* **Social vulnerability index** <https://www.atsdr.cdc.gov/placeandhealth/svi/interactive_map.html>)
* **Eligible population**: According to the CDC recommendations, the targeted population for Phase 1 COVID-19 vaccination includes healthcare personnel, non-healthcare essential workers, adults with high-risk medical conditions, and adults over 65 years old (Dooling et al., 2021). Phase 1 was further divided into three subcategories: phases 1a, 1b, and 1c, with each phase lasting approximately five weeks (Dooling, 2020). Based on the total population of about 331,500,000, it is estimated that 24 million, 49 million, and 129 million unique individuals are eligible for vaccination in phases 1a, 1b, and 1c, respectively (*County Population by Characteristics: 2020-2021*, 2021; Dooling et al., 2021). As detailed data regarding the number of eligible individuals for vaccination in each county is unavailable, we utilized the aforementioned information to estimate that approximately 7.2%, 14.8%, and 38.9% of the population in each county qualifies for vaccination during phases 1a, 1b, and 1c, respectively. Overall, a total of 60.9% of the population becomes eligible for vaccination during phase 1.
* **Hospitalization and mortality by county** is downloaded from <https://data.cdc.gov/Case-Surveillance/COVID-19-Case-Surveillance-Public-Use-Data-with-Ge/n8mc-b4w4>
* **Estimate of minimum threshold:** For estimating , we have adopted the approach proposed by (Ochoa-Barragán et al., 2023) as presented by following formula.

: The rate of infected cases per each state during time period

: fraction of demand (i.e., eligible population for vaccination) that have underline conditions such as obesity, diabetes, hypertension, and heart failure. According to (O’hearn et al., 2021), approximately 63.5% of COVID-19 hospitalizations in the United States could be linked to these four underline conditions.

: number of hospitalizations.

: The COVID-19 mortality rates are obtained from (CDC, 2021) We assumed that these mortality rates are the same across all counties within each state.

# Vaccine allocation and distribution process

The CDC determines the allocation of vaccines to each state. Subsequently, each state takes on the responsibility of managing the distribution of the allocated doses among their approved providers who have placed orders. The vaccination programs in each state approves the orders placed by providers based on several factors, including the estimated population that providers can serve, the providers' capacity to store and handle vaccines, and the existing inventory level.

The CDC may adjusts the number of vaccines allocated to each state over time, based on the increasing availability of supplies and the population recommended for vaccination by the Advisory Committee on Immunization Practices (ACIP). The approved orders will be shipped directly from vaccine manufacturers to providers by the CDC. Once a vaccine product has been shipped to a COVID-19 vaccination provider site, the federal government is not responsible for redistributing the product or covering the costs associated with redistribution. However, in cases where redistribution is necessary, such as for orders smaller than the minimum order size that the CDC does not directly ship to provider sites, the vaccination provider may be permitted to redistribute the vaccine if approved by the state's immunization program. Redistribution must be carried out in compliance with the manufacturer's instructions and the guidance provided by the CDC (CDC, 2020).



Figure 1. Process flow of vaccine allocation and distribution in the US.

# Results

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