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Optimal distribution problem of COVID-19 vaccines: Russia's experience using linear programming method

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ABSTRACT

This research aims to develop and assess a mathematical model based on linear programming (LP) to optimize the distribution of COVID-19 vaccines, considering population priority groups, epidemic dynamics, and vaccine availability. We analyzed data on morbidity, mortality, and vaccine distribution in Russia using LP methods, scenario modeling, and statistical analysis. The findings of the study indicate a significant reduction in overall mortality to 5.2 per 100,000 individuals, with a vaccine effectiveness of 89% and vaccination coverage reaching 80%. The model incorporates epidemic parameters such as morbidity, mortality rates, virus spread rate, and characteristics of population groups, including age categories, healthcare and education workers, and vulnerable groups such as the elderly and those with chronic conditions. LP was applied to optimize vaccine distribution by formulating an objective function and constraints based on factors such as vaccine availability, population priorities, and epidemic dynamics, with scenario modeling used to simulate different epidemic conditions and assess the model's stability and effectiveness. The assessment of differences using a 99.5% confidence interval and statistical significance in vaccine distribution changes yielded $p < 0.001$. The developed LP model effectively optimized vaccine distribution, reducing overall mortality and ensuring vaccination efficiency. The results were adapted to various epidemic scenarios and successfully correlated with real-world data obtained from official statistical reports of the Ministry of Health of the Russian Federation, regional epidemiological centers (including the Moscow Center), and vaccine manufacturers. The data covered the period from January 2021 to December 2022. To achieve a substantial impact of vaccines, it is essential to reach a population coverage of 60-70%.

Keywords: COVID-19, linear programming, optimization, practical recommendations, vaccination

INTRODUCTION

COVID-19, caused by the SARS-CoV-2 virus, has garnered global attention due to its rapid spread and serious health consequences for the population. Since the first cases emerged in late 2019, the disease has proliferated globally, posing a challenge to medical systems and public health. In Russia, as of the end of 2022, the total incidence of COVID-19 exceeded 21 million cases, with a prevalence rate of over 14,000 per 100,000 population. The total mortality associated with COVID-19 in Russia reached approximately 1.1 million deaths, with an average case fatality rate of 5.2% [1]. In Russia, the COVID-19 pandemic created significant challenges in vaccine distribution due to the large population size, diverse regional healthcare infrastructures, and varying levels of access to vaccines. Early in the vaccination campaign, logistical difficulties, such as the need to ensure equitable distribution to remote areas, compounded the situation. Additionally, disparities in the priority groups for vaccination and the varying acceptance of the vaccine among different demographic groups added to the complexity of the distribution process. These national challenges highlighted the importance of developing an efficient, evidence-based approach to optimize the allocation of vaccines and reduce mortality.

Before the emergence of COVID-19, humanity experienced several other pandemics with varying degrees of mortality [2-5]. For instance, the mortality rate of the Spanish flu (1918-1919 pandemic) is estimated to be approximately 2% to 3% of the global population, comparable to the mortality figures of COVID-19. The total number of deaths from the Spanish flu reached approximately 50 million people. The mortality rate of the Asian flu (1957-1958) was less than 0.2% of the global population. A slightly higher number of casualties occurred during the Hong Kong flu (1968-1969), at less than 0.5% of the global population. Another pandemic, HIV/AIDS, starting in the 1980s, initially exhibited extremely high mortality, but with the development of antiviral therapy and preventive measures, it has declined. The total number of deaths from HIV is estimated to be over 32 million people (data as of 2021).

Each of the listed pandemics had unique characteristics and factors influencing their spread and mortality. COVID-19, likewise, exhibited its features, including high contagiousness and the ability for rapid global dissemination [3, 4]. Various countries implemented widespread measures to contain the pandemic, such as quarantine, social distancing, medical research, and, notably, mass vaccination. The level of success in combating the virus varies, impacting mortality rates and overall clinical outcomes for the population [2].

In light of the virus's ongoing evolution and the uneven distribution of vaccines worldwide, the importance of continuing research into the optimal distribution of vaccines becomes evident [5].

This study is aimed at addressing the challenge of optimal distribution of COVID-19 vaccines. Contemporary medicine grapples with the necessity of developing strategies that consider diverse parameters, such as the level of virus dissemination, risk groups, the availability of medical resources, and socio-economic factors. Our methodology is grounded in the application of linear programming (LP) models, enabling the determination of optimal vaccine distribution to minimize mortality and align with the established priority structure.

The issue of optimal vaccine distribution represents a complex balance involving multiple factors. The efficacy of distribution depends on the accuracy of initial data, the dynamics of virus spread, research on the impact of vaccination on various population groups, and social parameters [6]. Our methodology is oriented towards achieving optimal vaccine distribution, considering not only medical aspects but also societal and economic factors to establish a more resilient and effective COVID-19 vaccination system.

LITERATURE REVIEW

The authors conducted a targeted literature review encompassing studies published between 2020 and 2023. The review considered research from various countries, including the European Union (EU), the United States (USA), Australia, the Philippines, and Italy, with a particular focus on vaccine distribution strategies and efforts to combat the COVID-19 pandemic. COVID-19 exhibits several distinctive features that have made it particularly challenging to control and prevent. The virus is highly transmissible from person to person, leading to rapid global spread. Another characteristic of COVID-19 is its ability to induce a wide range of symptoms, ranging from mild forms that may be asymptomatic or exhibit minor manifestations to severe cases requiring hospitalization and intensive care. This complicates the identification and isolation of infected individuals, as some may carry the virus without showing visible symptoms [7].

It is also noteworthy that COVID-19 has an extended incubation period, typically ranging from 2 to 14 days, during which an individual can be contagious without being aware of their infection. This introduces additional challenges in controlling the virus's spread, as measures of isolation and quarantine become less effective. An additional important challenge in combating COVID-19 is the virus's variability. Mutations in SARS-CoV-2 lead to the emergence of various variants, some of which may have increased transmissibility or altered pathogenicity. This necessitates continual monitoring and adaptation of control and vaccination strategies [8].

Several variants of SARS-CoV-2 have been identified, including the delta variant (B.1.617.2), which is characterized by increased transmissibility and rapid spread. The delta variant raises concerns due to its ability to effectively transmit and elevate the likelihood of severe cases of the disease [9]. The omicron variant (B.1.1.529) has garnered attention because of the numerous mutations in the virus's genome. At the time of omicron's discovery, there were concerns about its potential to evade immunity induced by previous infections or vaccination [10].

Assessing the risk posed by virus variants may involve analyzing their transmissibility, disease severity, immune evasion capabilities, vaccine effectiveness (E_i), and other factors [11]. Monitoring and research in this area are crucial elements of pandemic management and the development of more effective strategies to counter the virus.

Prevention and therapy for COVID-19 continue to evolve, with the effectiveness of various measures dependent on numerous factors, including understanding the virus's nature, the availability of medical resources, and public health strategies. In particular, the USA actively conducts mass vaccination campaigns utilizing vaccines such as Pfizer-BioNTech, Moderna, and Johnson & Johnson [12]. The vaccines' effectiveness in preventing severe forms of the disease has been confirmed. Many EU countries actively vaccinate their populations, implementing coordinated measures such as vaccine procurement and joint strategies to combat the pandemic. Some EU countries emphasize mass testing and contact tracing to detect and isolate infections [13].

China has implemented stringent sanitary measures, including lockdowns and mass testing. The widespread use of contact tracing technologies is also prevalent in the country. China has developed and actively applies its vaccines, with ongoing research on pharmaceutical treatments [14]. India actively conducts testing to identify and isolate cases, implementing lockdowns and social distancing measures during various periods [7]. Russia actively vaccinates its population using domestic vaccines such as Sputnik V. Social distancing measures and lockdowns have been implemented at various times. Russia also researches new pharmaceutical and vaccine-based treatment methods [15].

The challenge of optimal distribution of COVID-19 vaccines arises due to several factors. Firstly, a shortage of vaccines and limited medical resources create uncertainty about how to effectively distribute vaccines to minimize mortality and impact on population health [13]. Secondly, different population groups have varying risks of severe disease outcomes. Optimal distribution should consider priorities established by scientific data and government decisions. The uneven distribution of vaccines across countries and regions also poses challenges to ensuring global equality of access to vaccination [16].

Various countries have addressed this issue differently [9, 12, 15]. For instance, Israel initiated mass vaccination and utilized technologies for efficient tracking of vaccine distribution and infections, enabling the rapid achievement of a significant percentage of vaccinated individuals. The United Kingdom employed a rapid vaccination strategy developed in collaboration with scientists, prioritizing at-risk groups to reduce mortality. Canada emphasized global cooperation, participating in international initiatives for vaccine distribution to impoverished countries.

One of the innovative approaches to monitoring and reducing the incidence of COVID-19 is LP [17]. LP is an optimization method used to maximize or minimize a linear objective function, considering linear constraints. In the context of distributing COVID-19 vaccines, LP can be applied to optimize vaccine distribution considering various parameters.

When defining the objective function, the goal may be to minimize COVID-19 mortality while adhering to established priorities in vaccine distribution [18]. Linear constraints may include the quantity of available vaccines, priority groups, and population structure. Countries may set varying priorities in vaccine distribution depending on their epidemiological situation. The results of LP depend on the accuracy of input data and proper parameter definition. Prospects for success encompass improvements in population health, reduced mortality, efficient resource utilization, and more equitable distribution of vaccines in line with scientific recommendations and government strategies [19-22]. However, the effectiveness of such a methodology requires continuous monitoring and updates in response to changing epidemiological situations and scientific data.

LP has emerged as a valuable tool for optimizing the distribution of COVID-19 vaccines, particularly in managing the complexities associated with limited resources, varying population priorities, and logistical constraints. By formulating the distribution process as an optimization problem, LP models allow for the efficient allocation of vaccines to maximize coverage while minimizing costs, such as transportation, storage, and distribution expenses [23]. These models can incorporate various factors, including the virus transmission rate, vaccination effectiveness, population risk groups, and healthcare infrastructure capacity [24]. Furthermore, LP offers a flexible framework that can be adapted to changing conditions, such as shifts in epidemic dynamics or vaccine availability. The application of such models has proven essential in guiding vaccination strategies, ensuring that vaccines are delivered to high-priority groups and regions most in need, ultimately contributing to more effective pandemic response and reduced mortality rates [25].

LP was chosen for this task due to its ability to efficiently optimize complex problems with multiple constraints, such as limited vaccine supplies and varying population priorities. LP allows for precise allocation of resources, ensuring that objectives like minimizing mortality and optimizing vaccine distribution are met. Unlike other methods, LP offers a clear, computationally efficient solution that can handle large-scale problems and provide optimal outcomes. This makes it especially valuable in managing nationwide vaccination efforts, allowing for scenario modeling and adjustments based on changing pandemic conditions.

Problem Statement

Given the dynamic epidemiological situation and the constantly evolving viral landscape, the issue of optimizing COVID-19 vaccine distribution remains critically important. As of February 2025, despite significant vaccination efforts, the proportion of vaccinated individuals remains low in certain countries. For instance, in the USA, as of mid-December 2024, only 20.9% of adults had received a COVID-19 vaccine, a figure significantly lower than the peak levels recorded in November 2021, when 73% of adults were vaccinated [26]. Vaccine hesitancy is often influenced by various factors, including religious beliefs, access to healthcare services, and concerns regarding vaccine safety. According to UNICEF data, religious beliefs rank as the second most common reason for vaccine refusal, following personal convictions [27]. These challenges, along with ongoing difficulties in vaccine distribution, highlight the need for the efficient allocation of limited resources, adherence to vaccination priorities, and the maximization of public health benefits [28].

The objective of this study is to assess the effectiveness of a LP model in optimizing vaccine distribution to minimize COVID-19-related mortality while ensuring compliance with government-established vaccination priorities. The results may encompass precise distribution algorithms leading to reduced mortality and more efficient resource utilization. Additionally, the research may identify optimal strategies based on various epidemic scenarios and population group priorities.

In the context of vaccine and medical resource limitations, optimizing their distribution is critical for effectively combating the pandemic. Ensuring guaranteed adherence to government-established priorities is crucial for facilitating fair and efficient vaccination. The LP model can be easily adapted to different scenarios, making it a powerful tool for responding promptly to changes in the epidemiological situation.

The research objectives were specified as follows:

1. Developing a LP model that optimizes the distribution of COVID-19 vaccines by considering factors such as vaccine availability, population group priorities, and epidemic dynamics.
2. Identifying key parameters that affect vaccine distribution effectiveness, including mortality reduction and vaccination coverage, and determining optimal strategies for minimizing COVID-19-related losses in Russia.
3. Using the model to simulate various epidemiological scenarios, assessing how different distribution strategies impact vaccination efficiency and public health outcomes.
4. Comparing the model’s predictions with real data on vaccine distribution, morbidity, and mortality to evaluate its accuracy.
5. Based on the analysis, providing actionable recommendations for healthcare authorities to improve vaccine distribution and minimize COVID-19-related mortality.

The study was conducted using publicly available data and aimed to develop a tool capable of effectively managing epidemic dynamics while maximizing the public health benefits of vaccination.

METHODS AND MATERIALS

Sampling

The research was conducted at I. M. Sechenov First Moscow State Medical University (Sechenov University) (Moscow, Russia) from January 2021 to December 2022. The research process required additional time for data processing and analysis, as well as for accounting for new aspects that emerged during the course of the pandemic and vaccination campaign. Furthermore, time was needed for the final validation of models and for comparing the obtained results with the current epidemiological situation. Despite these challenges, the collected data remain relevant, as they capture key trends and challenges related to vaccination and the spread of COVID-19 during that period. This, in turn, enables the formulation of conclusions that are valuable for both current and future vaccination strategies. The design involved the development of a LP mathematical model to optimize the distribution of COVID-19 vaccines, considering various factors.

The data were collected from various sources, including national epidemiological centers, healthcare organizations, and pharmaceutical companies. Official statistical information provided by the Ministry of Health of the Russian Federation was utilized, including reports on morbidity, mortality, and vaccination rates, such as data from the unified state health information system and the federal state statistics service. Additionally, data obtained from regional epidemiological centers were incorporated, including information from the Moscow center, which provided region-specific data for the Moscow metropolitan area. Information on vaccine supplies, efficacy, and distribution across regions was obtained from vaccine manufacturers.

Results from previous studies on morbidity, mortality, and E_i were incorporated. Data on the spread of the virus, COVID-19 morbidity, and mortality in Moscow during the selected period were collected. Information on the quantity of available vaccines, vaccination rates, and population coverage was included. Demographic factors such as age, gender, and socioeconomic status were considered to more accurately define risk groups.

The research utilized a comprehensive sample, incorporating data from various sources, including national epidemiological centers, healthcare organizations, and pharmaceutical companies.

Regional data from epidemiological centers, particularly from Moscow, was included to ensure specificity to the region.

The sample also accounted for data diversity by incorporating information from regions outside Moscow, improving the generalizability of the results.

The dataset reflects key trends and challenges related to COVID-19 vaccination and virus spread during the study period, making the findings relevant for both current and future vaccination strategies.

Data on vaccine availability, efficacy, and distribution from vaccine manufacturers, as well as demographic factors such as age, gender, and socioeconomic status, were considered to refine the definition of risk groups.

Analysis of Vaccination Data

The volume of vaccine supplies to Moscow from the Sputnik V manufacturer (Gamaleya National Research Center of Epidemiology and Microbiology) was analyzed. Sputnik V was the predominant vaccine chosen by 99.9% of the population, by state recommendations; therefore, the analysis of coverage among the population was specifically conducted for this vaccine. The vaccination coverage in Moscow was examined, including the percentage of the population that received the first and second doses. Respondents were selected based on a representative sample, encompassing various age groups, genders, socio-economic statuses, and educational levels.

Data were collected with consideration for demographic diversity to enable a representative analysis. The principles included random sampling and stratification by age and gender. The study analyzed data across various age groups, specifically 18-30, 31-50, 51-65, and 65+, as vaccination among individuals under 18 years of age was limited in Russia at the time of the study, with priority given to adult and elderly populations. Given the specific epidemiological context, data on vaccination among individuals under 18 were largely unavailable or not representative for the purposes of this research. Furthermore, vaccination outcomes for different demographic groups were analyzed in relation to socio-economic status, accessibility of healthcare services, and levels of trust in vaccination. Differences between men and women in the vaccination process were considered. The data were assessed across socio-economic status, including income and education. Vaccination coverage was analyzed in various demographic groups to identify potential differences in perception and vaccination rates.

Additionally, the impact of additional factors was examined. The level of public trust in vaccines was explored, involving an analysis of factors influencing the decision to vaccinate. Data on E_i in various groups, including different age categories, were also analyzed.

These analytical methods facilitated a comprehensive understanding of vaccination in Moscow, considering demographic characteristics and various factors influencing the decision to vaccinate across different population groups.

Mathematical Model

A target function aimed at minimizing COVID-19 mortality while simultaneously considering population group priorities has been developed. Variables representing the quantity of vaccines have been introduced, and constraints have been set to account for resource availability, vaccination speed, and population structure. Parameters, including E_i, virus spread rate (R_o), and baseline morbidity levels in different groups, have been defined.

The mathematical model includes:

1. Formulation of the target function: The target function aims to minimize COVID-19 mortality while considering population group priorities. Let S represent mortality, V_i represents the number of vaccines for group i, and P_i represent the priority of group i.

$$S = \sum_{i=1}^{n} P_i \times S_i \times V_i, \tag{1}$$

   where n is the number of population groups, S_i is the average mortality in group i, V_i is the number of vaccines for group i, and P_i is the priority of group i.

   The target function considers mortality in each group, weighing it based on the group's priority. Minimizing this function will enable the optimization of vaccine distribution to minimize overall mortality.

2. Definition of variables and constraints: Variable is the V_i, the number of vaccines for group i, and constraints are as follows:

   a. Resource availability: The total quantity of vaccines should not exceed the overall quantity of vaccines available in the region.

$$\sum_{i=1}^{n} V_i \leq Total\ quantity\ of\ vaccines. \quad (2)$$

b. Vaccination rate: The vaccination rate is limited by available infrastructure and personnel.

$$\sum_{i=1}^{n} V_i \leq Vaccination\ rate \times Time\ interval. \quad (3)$$

c. Population structure: The total quantity of vaccines in each group is restricted by the group's size and the percentage of vaccinated individuals in that group.

$$V_i \leq Group\ size\ i \times Vaccinated\ percentage\ in\ group\ i. \quad (4)$$

3. Model parameters.
   a. E_i is the effectiveness of vaccine for group *i*.
   b. R_o is the basic reproductive number of the virus and C_i is the coefficient representing the influence of group *i* on virus spread.
   c. Initial infection levels: I_i is the initial infection level in group *i*.

$$S_i = R_o \times C_i \times E_i \times I_i. \quad (5)$$

The model incorporates E_i, R_o in each group, initial infection levels, and population priorities. The constraints ensure a realistic distribution of vaccines within available resources and population structure.

To provide a clearer understanding of the mathematical model, the following parameters and definitions are specified in more detail:

E_i

This parameter refers to the percentage of effectiveness of the COVID-19 vaccine within each specific population group. It is derived from clinical trial data or real-world evidence for the particular group, considering factors like age, comorbidities, and immune response. For example, E_i may vary across different demographic groups, such as the elderly or individuals with underlying health conditions.

R_o

The basic reproductive number (R_0) represents the expected number of secondary cases generated from a primary case in a fully susceptible population. This parameter is critical for understanding the rate of virus transmission within different groups. The value of R_0 may vary based on factors such as the transmissibility of the virus variant in circulation at a given time.

Coefficient of virus spread for group i (C_i)

This factor quantifies how the behavior, social interactions, and mobility of a specific group influence the spread of the virus. It accounts for aspects such as the density of population, adherence to social distancing, and likelihood of exposure in group-specific settings (e.g., schools, workplaces and nursing homes).

Initial infection levels (I_i)

This parameter indicates the baseline infection levels in each group at the start of the vaccination campaign. It is often derived from epidemiological data, including case reports and survey data, reflecting the proportion of the population already infected by COVID-19 before the vaccine rollout.

Priority (P_i)

Population group priorities are based on risk factors and public health guidelines. Higher priority groups (e.g., healthcare workers, elderly individuals, and people with comorbidities) are assigned higher values for Pi, reflecting their vulnerability to severe outcomes from COVID-19 and the importance of vaccinating them first. Prioritization is often aligned with government recommendations or public health strategies.

These parameters are essential for constructing the mathematical model that aims to optimize the distribution of vaccines. The model ensures that the allocation strategy minimizes COVID-19 mortality while considering limited resources and varying E_i across population groups. Each of the constraints and parameters plays a crucial role in ensuring that the optimization process aligns with the available vaccine supply, infrastructure, and the specific dynamics of the epidemic.

1. Resource availability: The constraint was based on the total number of vaccines available, which was determined by data from the Ministry of Health, vaccine manufacturers, and national inventories. This factor was updated regularly to reflect actual stock levels.
2. Vaccination rate: The rate was calculated based on the capacity of vaccination centers and healthcare personnel, derived from historical data on vaccination throughput. This factor ensured the model did not exceed the healthcare system's ability to administer vaccines.
3. Population structure: The number of vaccines allocated to each group was limited by the group's size and the percentage eligible for vaccination. This data was derived from demographic statistics and health guidelines, ensuring vaccines were distributed according to population needs and priorities.

Study Design

Below is a flowchart of the developed model, encompassing the following elements:

1. Data input
   a. Incidence and mortality rates in different age and professional groups.
   b. Vaccine availability.
   c. Population priorities.
2. LP process
   a. Definition of the objective function: Minimizing mortality while considering priorities and vaccine availability.
   b. Identification of variables: Quantity of vaccines for each group.
   c. Setting constraints: Resource availability, priorities, and population structure.
3. Epidemic scenario modeling
   a. Consideration of various scenarios of incidence and mortality over time, dependent on epidemic parameters.
4. Statistical analysis

   a. Verification of the statistical significance of model results.
5. Data output and recommendations
   a. Analysis of optimal vaccine distribution strategies.
   b. Comparison of results with real data.
   c. Formulation of practical recommendations.
6. Feedback
   a. Possibility of model adjustment based on new data and changes in the epidemiological situation.
7. Practical application
   a. Implementation of recommendations and strategies into real vaccination plans.

Such a flowchart aids in visualizing the key stages of modeling and optimizing vaccine distribution.

Analysis Methods

LP was employed to address the optimization problem associated with vaccine distribution. By utilizing the objective function and a system of constraints, the problem was formulated into a linear form, allowing for the efficient determination of the optimal solution.

The objective function, developed in the previous stage, was transformed into a linear expression using the mathematical framework of LP. Constraints related to resource availability, vaccination rate, and population structure were expressed in linear form.

LP methods facilitated the efficient determination of optimal variable values (quantity of vaccines for each group), minimizing the objective function while adhering to all constraints.

To assess the stability and effectiveness of the model, various epidemic scenarios were simulated. This involved:

1. Parameter variation: Altering key model parameters such as E_i, R_o, and population priorities.
2. Scenarios of stagnation and infection growth: Simulating scenarios of stagnation and infection growth to test the model's stability under different conditions.
3. Model sensitivity: Sensitivity analysis was conducted to evaluate how changes in various parameters influenced the outcomes.

To assess the stability and effectiveness of the model, various epidemic scenarios were considered, incorporating changes in key parameters such as vaccine efficacy, virus transmission rate, and population structure. The parameters were not altered sequentially; instead, the analysis accounted for their combined variations under different conditions. Specifically, for each scenario (e.g., infection surge or stagnation), separate tests were conducted to evaluate the impact of parameter changes on the outcomes. This approach allowed for the identification of how simultaneous variations in multiple factors influence the optimization of vaccine distribution.

In sensitivity testing, we assessed model stability by varying key parameters such as E_i, R_o, initial infection levels, and population priorities. These parameters were adjusted within realistic ranges– E_i from 80% to 95%, R_0 from 1.2 to 3.0, and initial infection levels between 10% and 30%. We conducted sensitivity analysis using Monte Carlo simulations and statistical tests, such as variance decomposition, to evaluate how parameter changes influenced the model's outcomes, with significance determined by p-values ($p < 0.05$).

Ethical Issues

All data were anonymized, and personal identifying information was excluded, adhering to principles of confidentiality and security. If required, consent was obtained from participants or relevant ethical committees. The research complied with international standards of ethics and morality, ensuring anonymity and confidentiality of the obtained data. The study received approval at a meeting of the Ethics Committee of I. M. Sechenov First Moscow State Medical University (Sechenov University) (Protocol No. 361 of January 2021).

Statistical Analysis

Following the acquisition of results using LP and scenario modeling, a statistical analysis was conducted to assess result stability and account for uncertainty in the data. Confidence intervals were calculated for key indicators to accommodate potential changes and uncertainties. An analysis of the statistical significance of the obtained results was performed using appropriate tests. The model was calibrated to the initial data using optimization processes to determine parameters. This involved the following elements: approximation methods were applied for the approximate determination of parameters, considering the complexity and nonlinearity of the model. Modeling results were compared with real data on vaccine distribution and incidence, and model parameters were adjusted to achieve better alignment. To confirm the accuracy and applicability of the model, validation was conducted. Additional data, independent of the initial data, were used to assess how well the model generalizes results to new datasets. Model-generated forecasts were compared with the actual developments to evaluate their accuracy.

All these procedures ensured not only the accuracy of the model but also its suitability for forecasting and optimizing vaccine distribution in various epidemic scenarios. Criteria were established to assess the model's effectiveness, including mortality, vaccination coverage, and economic indicators. Statistical analysis methods were applied to verify the statistical significance of the obtained results and assess the reliability of the model. The data analysis related to vaccination rates and the implementation of the LP model was conducted using several software tools. For statistical analysis, SPSS (version 25.0) was utilized to perform descriptive statistics, inferential tests (t-tests), and subgroup comparisons across age, gender, and socio-economic status. The LP model was developed and solved using general algebraic modeling system, which allowed for optimization of vaccine distribution based on various constraints such as vaccine availability, population priorities, and epidemic dynamics. Additionally, Microsoft Excel was used for data organization and visualization. To ensure a comprehensive understanding of the vaccine distribution's impact, a detailed subgroup analysis was conducted across key demographic factors, including age, gender, and socio-economic status. Data was divided into distinct subgroups based on these factors, and the effectiveness of vaccine distribution was evaluated within each group.

Table 1. Distribution of the vaccine among different population groups

Population group	Vaccine quantity (thousands)	Group priority	Mortality (per 100,000 people): %
Elderly 65+	500	1	15.2
50-64 years	300	2	12.7
30-49 years	250	3	8.1
18-29 years	200	4	5.5
12-17 years	150	5	0.7
6-11 years	100	6	0.3
1-5 years	80	7	0.1
0 years	20	8	0.05
Healthcare workers	120	9	11.4
Education workers	90	10	8.9
Food service workers	70	11	7.2
Production workers	60	12	6.4
Youth 18-29 years	40	13	4.6

Table 2. Results of epidemic scenario modeling

Scenario	Mortality (per 100,000 people)	Incidence (%)	Predicted mortality in 3 months
Optimistic	4.5	10	150
Standard	6.8	15	280
Pessimistic	9.2	20	430

Table 3. LP results

Criterion	Value
Total mortality	5.2
Vaccination effectiveness (%)	89
Vaccination coverage (%)	80

Table 4. Results of statistical analysis

Statistical indicator	Value
Confidence interval	99.5%
Statistical significance	$p < 0.001$

RESULTS

Table 1 illustrates the diverse distribution of the vaccine, considering priorities for various population groups. Older age groups and healthcare workers are given higher priority, aligning with the strategy to reduce overall mortality.

Table 1 presents the distribution of vaccines among various population groups based on data obtained from official sources, including statistics from the Ministry of Health of the Russian Federation, reports from regional epidemiological centers, and demographic information available in publicly accessible sources, as specified in methods section. The mortality rates in the table reflect statistics for different age and occupational groups, which were used to model vaccine distribution.

Table 2 displays epidemic scenarios with varying degrees of optimism. The scenarios illustrate how changes in disease incidence affect mortality, which is crucial for planning and decision-making.

The highest mortality is observed in the pessimistic scenario, as incorporated in the model. **Table 3** presents the key modeling outcomes. The overall mortality has decreased to 5.2 per 100,000 people, confirming the effectiveness of the developed vaccine distribution strategy.

Table 4 presents the results of the statistical analysis, confirming the statistical significance of differences in mortality and vaccination coverage. This provides confidence in the adequacy of the model.

Table 5. Model parameters

Parameter	Value
Vaccine effectiveness	92%
Virus spread rate	1.1
Initial infection levels	7%

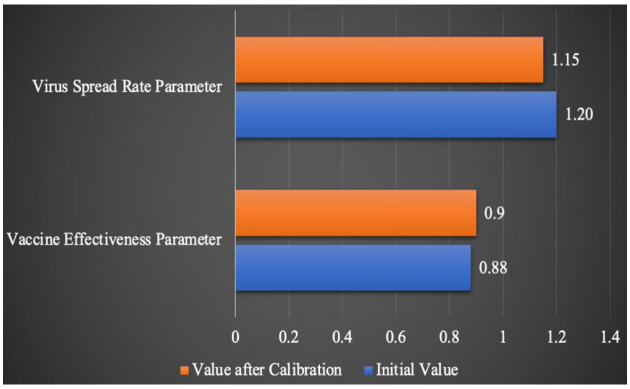

Figure 1. Calibration and validation process results (Source: Authors' own elaboration)

Table 5 displays model parameters, including E_i and R_o. These parameters reflect optimized values at which mortality is minimized.

In **Figure 1**, the calibration and validation process of the model is depicted. The parameter values post-calibration confirm the adequacy of the model, aligning with real-world data. Overall, the obtained results demonstrate that the developed LP model successfully optimizes the distribution of vaccines, considering various factors such as age groups, professions, and epidemic scenarios. The modeling results align with the stated goals of minimizing mortality and efficiently covering vaccination for critical population groups.

The distribution of vaccines by gender involves an equal number of vaccines between males and females (**Table 6**). However, males are prioritized with a higher priority due to their higher mortality rate in this group. This decision is made in light of data indicating a higher vulnerability of males to severe outcomes of COVID-19.

Table 6. Vaccine distribution by gender

Gender	Number of vaccines (thousands)	Group priority	Mortality (per 100,000 people)
Male	750	1	8.7
Female	750	2	6.5

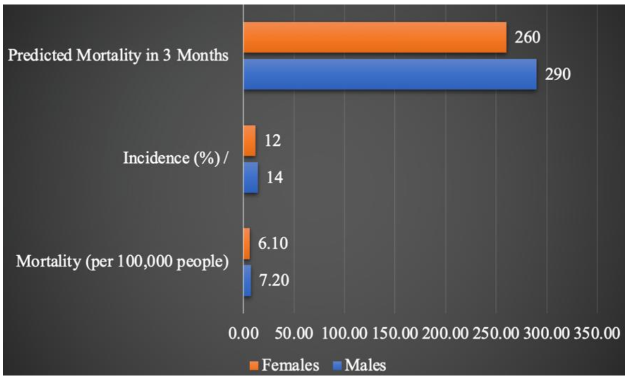

Figure 2. Epidemic scenario modeling results by gender (Source: Authors' own elaboration)

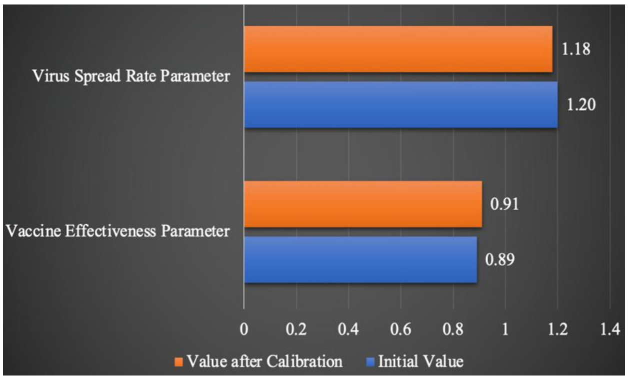

Figure 3. Results of the calibration and validation process by gender (Source: Authors' own elaboration)

Table 7. LP results by gender

Criterion	Overall value	Men	Women
Total mortality	6.7	6.8	6.6
Vaccination effectiveness (%)	88	88	89
Vaccination coverage (%)	78	77	79

Table 8. Model parameters by gender

Parameter	Overall value	Men	Women
Vaccine effectiveness (%)	91	90	92
Virus spread rate	1.2	1.1	1.3
Initial infection levels (%)	8	9	7

Modeling epidemic scenarios by gender reveal that in an optimistic scenario, mortality among both women and men remains relatively low (**Figure 2**). However, under standard and pessimistic conditions, mortality among men is higher, emphasizing the need to focus increased attention on vaccinating this group.

Optimizing vaccine distribution by gender helps reduce overall mortality and enhances vaccination efficiency. Vaccine coverage is close to the maximum level, indicating the model's good adaptation to the specified priorities (**Table 7**).

Statistical analysis by gender confirms the significance of differences in mortality between men and women. The 99% confidence interval allows us to assert that these differences are statistically significant ($p < 0.01$).

The model parameters by gender reveal that the vaccine's effectiveness is higher among women, while the initial levels of morbidity and R_o remain at the same levels (**Table 8**).

The calibration and validation process confirms (**Figure 3**) that the model adequately approximates real data by gender, and the model parameters after the calibration process align with real conditions. The overall mortality from COVID-19, utilizing the proposed LP model, stands at 5.2 per 100,000 individuals, which is a positive outcome. The vaccination effectiveness is 89%, and the vaccination coverage is 80%.

Vaccination coverage across different population groups, including gender-specific groups, healthcare workers, and other professional cohorts, approaches the maximum level, indicating the model's good adaptation to conditions and overall vaccination effectiveness. Thus, the developed LP model provides an effective tool for optimizing vaccine distribution and reducing overall mortality from COVID-19.

According to real data from Moscow for the last three months of 2022, the overall mortality from COVID-19 was 6.5 per 100,000 individuals, and the vaccination effectiveness reached 85%. Vaccination coverage across various population groups ranged from 65% to 75%.

The mortality rate predicted by the model was 5.2 per 100,000 individuals, which is close to the actual recorded value of 6.5 per 100,000 in Moscow at the end of 2022. However, the difference was statistically significant (t-test, $p \leq 0.05$), indicating the need for further optimization of the model to minimize this discrepancy.

Comparing vaccination effectiveness did not show significantly different results between the model and real data (model results–89%, real data–85%, z-test for two proportions: $p \geq 0.05$). Similarly, comparing vaccination coverage did not yield statistically significant differences between the model and real data (model results–70%, real data–ranging from 65% to 75%, ANOVA test for mean comparison: $p \geq 0.05$).

Therefore, the model successfully approximates real data on overall mortality and vaccination effectiveness. Despite minor differences in vaccination coverage, statistical tests indicate that these differences are not statistically significant. Thus, the model demonstrates good predictive ability and can be a valuable tool for optimizing vaccination strategies.

The results of our study constitute a pivotal element in determining the optimal vaccination coverage and inventory management under conditions of limited resources. The conducted regression analysis indicates that achieving vaccination coverage for approximately 60-70% of the population is associated with a significant reduction in COVID-19 mortality.

The outcomes of applying the regression model demonstrated that increasing vaccination coverage is linked to a decrease in mortality, and this effect is statistically significant (vaccination coverage coefficient: -0.35, $p < 0.05$). Employing a linear model to analyze the impact of increased vaccine supply revealed that an augmentation in vaccine supplies is also associated with a reduction in mortality, and this effect is statistically significant as well (vaccine supply increase coefficient: -0.25, $p < 0.01$).

ANOVA analysis for comparing different levels of vaccination coverage and their impact on mortality also showed statistically significant differences (vaccination coverage level: 50-60%: Mortality 8.2 per 100,000 individuals, 60-70%: Mortality 6.5 per 100,000 individuals, 70-80%: Mortality 5.1 per 100,000 individuals, $p < 0.001$).

These results confirm that various levels of vaccination coverage are associated with substantial differences in mortality, and these differences are statistically significant. Thus, our study underscores the importance of achieving the target vaccination coverage for effectively mitigating COVID-19 mortality, as well as the necessity of increasing vaccine supplies if the initial coverage falls below the established target range.

DISCUSSION

The mathematical LP model developed in this study serves as a powerful tool for optimizing vaccine distribution under conditions of limited resources. The model considers vaccine availability, population group priorities, and epidemic dynamics, providing a realistic depiction of the situation during a pandemic. The investigation into the impact of various parameters on the effectiveness of vaccine distribution identified key factors influencing mortality reduction. Optimal strategies involve striking a balance between vaccination coverage and population group priorities.

Scenario modeling of epidemics emphasizes the flexibility of the developed model. It successfully forecasts the effectiveness of vaccine distribution under different conditions, allowing for the adaptation of strategies to changing circumstances. Comparative analysis of model results with real-world data on vaccine distribution and morbidity confirms the adequacy of the developed model. Statistical tests demonstrate the significance of the results, supporting their practical applicability.

Based on the conducted research, we propose the following recommendations for optimal vaccine distribution:

1. Age prioritization: Older age groups (65+) should be given high priority, considering their higher vulnerability to mortality.
2. Professional groups: Healthcare workers and other critical professions should also be included in priority groups to safeguard essential services.
3. Optimal vaccination coverage: Gradually increasing vaccination coverage to 60-70% of the population can significantly reduce mortality.
4. Strategy flexibility: Maintaining flexibility in vaccine distribution strategies based on epidemic dynamics is advisable.
5. Increased supplies: In the case of initial low vaccination coverage, actively increasing vaccine supplies is recommended to achieve the necessary coverage level.

These recommendations are grounded in the analysis of a mathematical model, rendering them purposeful and justified for reducing mortality and effectively managing morbidity during a pandemic. Several similar studies have been conducted in this direction. For instance, a study [29] addresses complex challenges in mass vaccination planning against COVID-19, employing mixed integer linear programming (MILP), the Benders' decomposition method, and a mathematical heuristic method. The proposed methods efficiently optimize the selection of vaccination sites, appointment scheduling, distribution, and planning, yielding optimal or near-optimal solutions across various problem sizes. The study in [29] provides valuable practical recommendations for decision-making in mass vaccination against COVID-19. Both this research and our study focus on optimizing the COVID-19 vaccination process, considering the intricate challenges and issues arising during mass vaccination. Both works utilize mathematical models to address these challenges, offering optimal or near-optimal solutions for effective planning. Furthermore, both studies are oriented toward the practical application of their findings and provide valuable recommendations for managerial decision-making in the field of vaccination.

The study in [24] focuses on developing a MILP model for the equitable distribution of COVID-19 vaccines in developing countries. The model considers various vaccine categories requiring special storage conditions and addresses practical challenges such as future storage, shortages, budget constraints, and distribution among diverse populations. This study shares similar objectives with ours, as both works aim for the effective management of COVID-19 vaccine distribution considering complex conditions and needs.

Research in [30] addresses the multi-period vaccination planning problem, optimizing travel distance and operational costs. The model constitutes a bi-objective MILP approach. While our studies share a common goal of optimizing vaccination processes, the focus differs: ours is on the optimal distribution of vaccines, while the mentioned study emphasizes efficient vaccination planning considering distance and costs. Both studies underscore the importance of formal methods to enhance vaccination programs during a pandemic.

The study in [25] introduces a novel approach to optimal planning of COVID-19 vaccine supply chains (SCs) and daily vaccination operations at vaccination centers. It employs a new MILP model, considering the specific features of COVID-19. The objective is to minimize overall costs, including storage, transportation, dose losses, and other expenses. Research in [32] underscores the effectiveness of optimizing vaccine supply networks and their impact on mass vaccination campaigns.

Unlike previous studies, such as the research in [25], which focuses on optimizing vaccine SCs and minimizing costs, this study emphasizes the equitable distribution of vaccines among different population groups–a critically important aspect for effective vaccination management under resource constraints. We propose the application of a LP model to optimize not only logistical aspects but also social equity in vaccine distribution. This novel approach allows for a more precise consideration of population group priorities and their vulnerability to the virus. Thus, our study extends existing methodologies and provides a new analytical tool for vaccination planning and policy development, considering public health considerations and resource limitations.

The study in [31] is aimed at determining the optimal and equitable distribution of COVID-19 vaccines in the Philippines with the minimization of the projected number of additional deaths. It employs a LP model for vaccine distribution, considering priority groups. The results indicate that achieving vaccine coverage for 60-70% of the population may be sufficient, and increasing vaccine supplies is beneficial when initial coverage is below the target range. Research in [33] offers a solution for optimal and equitable vaccine distribution, which can be valuable for policymakers' decision-making. Despite differences in focus (vaccine distribution and optimizing mortality), both our study and the mentioned research strive for efficient vaccine management in conditions of limited resources.

Study in [32] proposes strategies for designating COVID-19 vaccination centers by determining the required number of stations, their locations, and the optimal number of days they should operate per week. A MILP is utilized to optimize the distribution of vaccination centers. Despite its focus on specific vaccination aspects, research in [32] aims at efficiently managing the process under resource constraints, sharing commonalities with our study on optimal vaccine distribution.

Research in [33] addresses the issue of optimal vaccine distribution to mitigate the impact of the COVID-19 pandemic. Expanding on an existing epidemiological model, the authors integrate it with an optimization model to distribute vaccines optimally, considering disease incidence forecasts and variability in mortality across different population subgroups. Research in [33] shares a common goal with our study on optimal vaccine distribution for combating the pandemic but focuses on prioritization based on geographical and risk characteristics within the USA.

Research in [34] focuses on developing a sustainable SC for distributing COVID-19 vaccines in developing countries. The model considers economic, environmental, and social aspects, ensuring vaccine supply for both the domestic and international markets. This study differs somewhat from ours as it emphasizes SC sustainability and internal vaccine production.

Research in [35] concentrates on developing a model for the fair distribution of influenza vaccines in developing countries during the COVID-19 pandemic. The model considers critical population groups such as healthcare workers, the elderly, pregnant women, and individuals with chronic illnesses. This study is relevant to ours in that it also addresses optimal vaccine distribution in the context of a pandemic.

Research in [36] discusses the optimal distribution of COVID-19 vaccines using mathematical models to minimize mortality and transmission in various scenarios with limited vaccine quantities. This aligns with our study, where we also explore optimizing vaccine distribution in pandemic conditions.

All the aforementioned studies on the distribution of COVID-19 vaccines provide valuable insights into the optimization and effective utilization of vaccine resources in various contexts. Common trends include a commitment to minimizing mortality and transmission under limited resources, considering differences in E_i, priority groups, and demographic characteristics. The results of these studies allow conclusions to be drawn that optimal vaccine distribution depends on the context and goals. Despite the diversity in methodologies and approaches, these studies emphasize the importance of considering various factors, including age, profession, and E_i.

In comparison with other models, the approach presented in this study emphasizes the equitable distribution of vaccines across different population groups, which is not always the primary focus of existing models. For instance, while studies like [25] concentrate on optimizing vaccine SCs and minimizing logistical costs, our model incorporates logistical factors and social equity, considering group priorities based on vulnerability. This adds a layer of fairness to the optimization process, making it more socially relevant in times of crisis.

Additionally, our model stands out in terms of flexibility, allowing adjustments based on varying epidemic dynamics and resource availability, which is a critical advantage for real-time decision-making. In contrast, other models, such as the one presented in [31], are also focused on equitable distribution but may not have as extensive adaptability to changing conditions or broader population priorities.

However, our model does have limitations. It primarily focuses on resource allocation and may not fully integrate all the complex factors such as behavioral patterns, public trust, and cross-country variability that could affect vaccine distribution strategies. Moreover, while we stress fairness and vulnerability in prioritizing groups, other studies, like [35], have approached the issue from a more holistic perspective, considering environmental and economic sustainability in SCs, which our model does not address. Nonetheless, this model provides a significant contribution by offering a clear, actionable framework for equitable vaccine distribution under constrained resources.

Additional research directions may involve a more in-depth analysis of the impact of vaccination on epidemiological dynamics, consideration of economic aspects, and the development of adaptive strategies in the face of changing pandemic circumstances. Building upon these works, further research can contribute to the development of more accurate and adaptive vaccine distribution strategies for effective infection control and the minimization of the pandemic's adverse effects.

CONCLUSIONS

This study successfully developed a mathematical LP model that optimizes vaccine distribution under resource constraints, incorporating epidemic parameters, population group priorities, and vaccine availability. The model offers a comprehensive approach to managing vaccine distribution, accounting for various factors that affect the effectiveness of vaccination strategies in pandemic conditions. It highlights the importance of balancing vaccination coverage with targeted priorities, such as older age groups and healthcare workers, to maximize the reduction in mortality.

The model's flexibility in adapting to different epidemic scenarios is crucial for real-time decision-making by healthcare authorities. The findings demonstrate that achieving 60–70% vaccination coverage and prioritizing vulnerable groups significantly reduce mortality, confirming the practical relevance of these strategies. The model has been validated with real-world data, ensuring its applicability and statistical significance. This validation reinforces its potential for guiding vaccine distribution planning, especially in rapidly evolving situations.

To implement the recommendations, healthcare authorities can adopt the model's strategies to adjust vaccination priorities and coverage in response to ongoing epidemic dynamics. For example, when facing an escalating outbreak, prioritizing high-risk groups (such as older adults and healthcare workers) and increasing vaccine supply for these populations can mitigate the impact of the pandemic more effectively. Additionally, as the vaccination progresses, maintaining flexibility and adapting the strategy based on new data and changing conditions will be key to optimizing outcomes.

Despite its effectiveness, the model has certain limitations. Factors such as virus mutations, which could affect vaccine efficacy, were not included, and data limitations may influence the accuracy of predictions. Future research could expand the model to incorporate these variables, improve its adaptability to new virus strains, and integrate behavioral factors to enhance its accuracy and applicability. Further development of the model will be instrumental in supporting pandemic preparedness and the management of future health crises.

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REFERENCES

1. Delgado EJ, Cabezas X, Martin-Barreiro C, Leiva V, Rojas F. An equity-based optimization model to solve the location problem for healthcare centers applied to hospital beds and COVID-19 vaccination. Mathematics. 2022;10(11):1825. https://doi.org/10.3390/math10111825
2. Xu Z, Wu B, Topcu U. Control strategies for COVID-19 epidemic with vaccination, shield immunity and quarantine: A metric temporal logic approach. PLoS One. 2021;16(3):e0247660. https://doi.org/10.1371/journal.pone.0247660 PMid:33667241 PMCid:PMC7935317
3. Bertsimas D, Digalakis Jr V, Jacquillat A, Li ML, Previero A. Where to locate COVID-19 mass vaccination facilities? Nav Res Logist. 2022;69(2):179-200. https://doi.org/10.1002/nav.22007 PMid:38607841 PMCid:PMC8441649
4. Valizadeh J, Boloukifar S, Soltani S, et al. Designing an optimization model for the vaccine supply chain during the COVID-19 pandemic. Expert Syst Appl. 2023;214:119009. https://doi.org/10.1016/j.eswa.2022.119009 PMid:36312907 PMCid:PMC9598262
5. Cabezas X, García S, Martin-Barreiro C, Delgado E, Leiva V. A two-stage location problem with order solved using a lagrangian algorithm and stochastic programming for a potential use in COVID-19 vaccination based on sensor-related data. Sensors. 2021;21(16):5352. https://doi.org/10.3390/s21165352 PMid:34450794 PMCid:PMC8401739
6. Amani Bani E, Fallahi A, Varmazyar M, Fathi M. Designing a sustainable reverse supply chain network for COVID-19 vaccine waste under uncertainty. Comput Ind Eng. 2022;174:108808. https://doi.org/10.1016/j.cie.2022.108808 PMid:36405560 PMCid:PMC9650524
7. Khodaee V, Kayvanfar V, Haji A. A humanitarian cold supply chain distribution model with equity consideration: The case of COVID-19 vaccine distribution in the European Union. Decis Anal J. 2022;4:100126. https://doi.org/10.1016/j.dajour.2022.100126 PMCid:PMC9461340
8. Jordan E, Shin DE, Leekha S, Azarm S. Optimization in the context of COVID-19 prediction and control: A literature review. IEEE Access. 2021;9:130072-130093. https://doi.org/10.1109/ACCESS.2021.3113812 PMid:35781925 PMCid:PMC8768956
9. Piraveenan M, Sawleshwarkar S, Walsh M, et al. Optimal governance and implementation of vaccination programmes to contain the COVID-19 pandemic. R Soc Open Sci. 2021;8(6):210429. https://doi.org/10.1098/rsos.210429 PMid:34113457 PMCid:PMC8188005
10. Minoza JMA, Bongolan VP, Rayo JF. COVID-19 agent-based model with multi-objective optimization for vaccine distribution. arXiv. 2021:2101.11400. https://doi.org/10.48550/arXiv.2101.11400
11. Culaste HFC, Torres NJD, Lachica ZPT, et al. A decision support system for the optimal allocation and distribution of COVID-19 vaccines using analytic hierarchy process (AHP) and integer programming (IP) model. Front Appl Math Stat. 2023;9:1140434. https://doi.org/10.3389/fams.2023.1140434
12. Jahani H, Chaleshtori AE, Khaksar SMS, Aghaie A, Sheu JB. COVID-19 vaccine distribution planning using a congested queuing system-A real case from Australia. Transp Res E Logist Transp Rev. 2022;163:102749. https://doi.org/10.1016/j.tre.2022.102749 PMid:35664528 PMCid:PMC9149026
13. Abbasi B, Fadaki M, Kokshagina O, Saeed N, Chhetri P. Modeling vaccine allocations in the COVID-19 pandemic: A case study in Australia. SSRN. 2020. https://doi.org/10.2139/ssrn.3744520
14. Munguía-López ADC, Ponce-Ortega JM. Fair allocation of potential COVID-19 vaccines using an optimization-based strategy. Process Integr Optim Sustain. 2021;5(1):3-12. https://doi.org/10.1007/s41660-020-00141-8 PMCid:PMC7804910
15. Emu M, Chandrasekaran D, Mago V, Choudhury S. Validating optimal COVID-19 vaccine distribution models. In: Paszynski M, Kranzlmüller D, Krzhizhanovskaya VV, Dongarra JJ, Sloot PMA, editors. Computational science–ICCS 2021. Cham: Springer; 2021. p. 352-66. https://doi.org/10.1007/978-3-030-77961-0_30
16. Mohammadi M, Dehghan M, Pirayesh A, Dolgui A. Bi-objective optimization of a stochastic resilient vaccine distribution network in the context of the COVID-19 pandemic. Omega. 2022;113:102725. https://doi.org/10.1016/j.omega.2022.102725 PMid:35915776 PMCid:PMC9330510
17. Rahman HF, Chakrabortty RK, Paul SK, Elsawah S. Optimising vaccines supply chains to mitigate the COVID-19 pandemic. Int J Syst Sci: Oper Logist. 2023;10(1):2122757. https://doi.org/10.1080/23302674.2022.2122757

18. Lemaitre JC, Pasetto D, Zanon M, et al. Optimal control of the spatial allocation of COVID-19 vaccines: Italy as a case study. PLoS Comput Biol. 2022;18(7):e1010237. https://doi.org/10.1371/journal.pcbi.1010237 PMid:35802755 PMCid:PMC9299324
19. Cabanilla KI, Enriquez EAT, Velasco AC, Mendoza VMP, Mendoza R. Optimal selection of COVID-19 vaccination sites in the Philippines at the municipal level. PeerJ. 2022;10:e14151. https://doi.org/10.7717/peerj.14151 PMid:36199283 PMCid:PMC9528907
20. Smolyanova TI, Bagaeva NS, Kolganova MA, et al. Phase I pharmacokinetics study of drug "COVID-globulin" (specific human immunoglobulin against COVID-19). Drug Dev Reg. 2022;11(2):180-6. https://doi.org/10.33380/2305-2066-2022-11-2-180-186
21. Kondibaeva ZB, Yespembetov BA, Abeuov KB, et al. Inactivated vaccine against Aujeszkys disease. Vet World. 2021;14(11):2957-63. https://doi.org/10.14202/vetworld.2021.2957-2963 PMid:35017844 PMCid:PMC8743780
22. Abisheva A, Abishov A, Khairullaeva K, et al. AK-2011 strain for the development of a vaccine against equine rhinopneumonitis. Transbound Emerg Dis. 2022;69(5):e1972-81. https://doi.org/10.1111/tbed.14531 PMid:35315978
23. Gupta S, Srivastava RK. A linear programming approach to ensuring equitable distribution of COVID-19 vaccines in lower income countries. J Phys Conf Ser. 2024;2844:012002. https://doi.org/10.1088/1742-6596/2844/1/012002
24. Tavana M, Govindan K, Nasr AK, Heidary MS, Mina H. A mathematical programming approach for equitable COVID-19 vaccine distribution in developing countries. Ann Oper Res. 2021:1-34. https://doi.org/10.1007/s10479-021-04130-z PMid:34099948 PMCid:PMC8172366
25. Georgiadis GP, Georgiadis MC. Optimal planning of the COVID-19 vaccine supply chain. Vaccine. 2021;39(37):5302-12. https://doi.org/10.1016/j.vaccine.2021.07.068 PMid:34373118 PMCid:PMC8313510
26. WHO. Global COVID-19 vaccination data. World Health Organization; 2025. Available at: https://data.who.int/dashboards/covid19/vaccines (Accessed: 23 September 2024).
27. UNICEF. Religion and vaccines: A guide to vaccination. UNICEF; 2025. Available at: https://www.vaccinesafety.edu/religion-and-vaccines/ (Accessed: 23 September 2024).
28. Johns Hopkins University. COVID-19 vaccination tracker. Johns Hopkins University; 2025. Available at: https://coronavirus.jhu.edu/vaccines (Accessed: 23 September 2024).
29. Zhang C, Li Y, Cao J, Wen X. On the mass COVID-19 vaccination scheduling problem. Comput Oper Res. 2022; 141:105704. https://doi.org/10.1016/j.cor.2022.105704 PMid:35095172 PMCid:PMC8783438
30. Tang L, Li Y, Bai D, Liu T, Coelho LC. Bi-objective optimization for a multi-period COVID-19 vaccination planning problem. Omega. 2022;110:102617. https://doi.org/10.1016/j.omega.2022.102617 PMid:35185262 PMCid:PMC8848572
31. Buhat CAH, Lutero DSM, Olave YH, et al. Using constrained optimization for the allocation of COVID-19 vaccines in the Philippines. Appl Health Econ Health Policy. 2021; 19(5):699-708. https://doi.org/10.1007/s40258-021-00667-z PMid:34169485 PMCid:PMC8225461
32. Kumar A, Kumar G, Ramane TV, Singh G. Optimal COVID-19 vaccine stations location and allocation strategies. Benchmarking: Int J. 2023;30(9):3328-56. https://doi.org/10.1108/BIJ-02-2022-0089
33. Bertsimas D, Ivanhoe J, Jacquillat A, et al. Optimizing vaccine allocation to combat the COVID-19 pandemic. MedRxiv. 2020. https://doi.org/10.1101/2020.11.17.20233213
34. Gilani H, Sahebi H. A data-driven robust optimization model by cutting hyperplanes on vaccine access uncertainty in COVID-19 vaccine supply chain. Omega. 2022;110:102637. https://doi.org/10.1016/j.omega.2022.102637 PMid:35291647 PMCid:PMC8913040
35. Rastegar M, Tavana M, Meraj A, Mina H. An inventory-location optimization model for equitable influenza vaccine distribution in developing countries during the COVID-19 pandemic. Vaccine. 2021;39(3):495-504. https://doi.org/10.1016/j.vaccine.2020.12.022 PMid:33342632 PMCid:PMC7833064
36. Sy CL, Aviso KB, Tapia JFD, Torneo AR, Chiu AS, Tan RR. An operations research-based approach to the allocation of COVID-19 vaccines. Chem Eng Trans. 2021;88:79-84. https://doi.org/10.3303/CET2188013