DOI https://doi.org/10.5281/zenodo.11087714

CLUSTER ANALYSIS FOR GEOGRAPHIC PRIORITIZATION OF COVID-19 VACCINATION IN THE STATE OF RIO DE JANEIRO

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Abstract

According to data compiled by the World Health Organization, by the second half of 2022, COVID-19 had caused approximately 15 million deaths globally. At the beginning of the pandemic in Brazil, the state of Rio de Janeiro was initially classified as the one with the highest lethality rate, registering one death for every 20 infected patients. In the initial phase of the vaccination campaign in this state, only 488,320 doses of the immunizer were made available in the first batch of the immunizer. The purpose of this study was to identify which municipalities should have received priority in the initial supply of the vaccine in the state, given that different cities showed significant disparities in the numbers of COVID-19 cases and deaths. Using data from the main epidemiological observatories, we sought to assess the expected impact on the number of years of life saved (YLS) – instead of lives saved – if there had been a prioritization in the distribution of vaccines in specific groups of municipalities through cluster analysis. The results indicated that concentrating vaccination in the municipality of Rio de Janeiro, to the detriment of the other conglomerates, would have more positive effects on the number of years saved. The primary contribution of this research lies in identifying effective practices for distributing vaccines in situations of scarce resources.

Keywords: Vaccine, COVID-19, Rio de Janeiro, Immunization Management, Cluster Analysis.

1 INTRODUCTION

In December 2019, the World Health Organization (WHO) was alerted to several cases of respiratory syndrome caused by an unidentified novel coronavirus in humans (OPAS, 2020). By January 30, 2020, the WHO had declared the coronavirus outbreak a “Public Health Emergency of International Concern” (OPAS, 2020), and the first confirmed case in Brazil was reported by the Ministry of Health on February 26, 2020. Recognizing the widespread geographical reach of the outbreak, the WHO declared the situation a pandemic on March 11, 2020 (Brazil, 2020).

As of August 7, 2020, Brazil had recorded over 100,000 COVID-19 deaths, with the toll now exceeding

700,000 and a fatality rate of 1.9%, per Ministry of Health data. Within this context, the state of Rio de Janeiro (RJ) is particularly notable, being the third most populous and the second largest economy in Brazil. According to the RJ State Government (Rio de Janeiro, 2022), the state has suffered over 70,000 deaths from approximately 2.2 million confirmed cases. Initially, Rio de Janeiro had the highest fatality rate in the country, with one death for every 20 infections, as reported by the Ministry of Health (Brazil, 2020).

The global race for a vaccine in 2020 marked a turning point, thanks to pharmaceutical endeavors and scientific collaboration. Brazil began its vaccination campaign on January 17, 2021, following emergency use authorization by the National Health Surveillance Agency (Anvisa), with Rio de Janeiro receiving its first shipment of 488,320 CoronaVac doses on January 19, 2021—less than 3% of the state's population.

Given WHO's vaccination guidelines favoring high-risk groups, Brazil faced the daunting task of prioritizing vaccine distribution amid limited supplies. Public officials grappled with decisions on allocating vaccines across demographic and professional groups to reduce mortality, meet public expectations, and uphold equity and fairness during an unprecedented health crisis.

This raises a pivotal question: Should there have been a strategic focus on prioritizing municipalities based on the variance in COVID-19 cases and death rates? And how about prioritizing years of life saved instead of more traditional criteria like lives saved? After all, is saving 100 lives of people with only a few years left to live equivalent to saving 100 lives of people with a longer remaining life expectancy?

This study examines the state of Rio de Janeiro, home to an estimated 16.3 million people, and analyzes data from the onset of the pandemic to January 19, 2021, the date when the initial doses of the CoronaVac vaccine were distributed.

2 THEORETICAL FRAMEWORKS

2.1 Epidemiology of SARS-CoV-2 in Rio de Janeiro

On March 5, 2020, the State Department of Health announced the first case of the novel coronavirus, COVID-19, in Rio de Janeiro—a 27-year-old individual who had recently traveled in Europe, specifically Italy and Germany. Within two months of identifying this initial case, the state reported over 1,000 COVID-19-related deaths, as per the State Health Department's records. Analysis of infection demographics revealed that individuals aged 30 to 39 were the most affected. However, the elderly, particularly those above 70, constituted the majority of mortality cases (Rio de Janeiro, 2021).

2.2 Scope of Public Management Responsibility across Different Levels during a Pandemic

The pandemic precipitated the imminent collapse of the country's health system, characterized by shortages of Intensive Care Unit (ICU) beds, medical equipment, essential supplies, and healthcare professionals—vital for the treatment of patients severely impacted by the virus (FIOCRUZ, 2021).

Article 6 of the 1988 Federal Constitution recognizes health as a fundamental social right. It mandates a collaborative approach among federal entities to ensure the provision of health services, in addition to education, food, work, housing, leisure, security, social welfare, maternity, childhood protection, and support for the underprivileged (Brazil, 1988).

In terms of vaccination, the National Immunization Program (PNI), established by Federal Law No. 6.259 (October 30, 1975) and Decree No. 78.321 (August 12, 1976), oversees the national vaccination strategy. The PNI's objectives include controlling, eradicating, and eliminating diseases preventable by vaccination. This program is heralded as a cornerstone of public health policy in Brazil and is credited with significantly reducing the incidence of various diseases (Brazil, 2011).

Furthermore, legal frameworks have addressed the constitutionality of mandatory COVID-19 vaccination. In December 2020, the Supreme Federal Court (STF), through the combined review of Direct Actions of Unconstitutionality (ADI) 6.586 and 6.587 and the Extraordinary Appeal with Appeal (ARE) 1.267.879, affirmed that the state possesses the authority to mandate COVID-19 vaccination, as stipulated in Article 3 of Law No. 13.979/2020. While physical vaccination cannot be enforced, the ruling permits the imposition of constraints (such as fines or restrictions on attending specific places or enrolling in educational institutions) on individuals refusing vaccination. The court's decision also confirmed the autonomy of states, the Federal District, and municipalities to conduct localized vaccination campaigns.

2.2.1 Criteria for COVID-19 Vaccine Distribution in Brazil

The arrival of the initial vaccine consignment in Brazil in January 2021 rekindled hope among the populace, eagerly awaiting relief from the multifaceted crises wrought by the pandemic, including its significant repercussions on education, mental health, domestic violence, and overall food security (Oliveira et al., 2020).

The deployment of the vaccination strategy was orchestrated on a tripartite basis, involving collaboration among the federal government, state governments, the Federal District, and municipalities. Given the impossibility of vaccinating the entire population simultaneously, the Brazilian government deliberated on prioritization criteria for the distribution of the COVID-19 vaccine. The primary aim was to minimize mortality rates and safeguard the labor force essential for the continuity of healthcare and other critical services (Brazil, 2021). To achieve this aim, one of the most used criteria around the world was a distribution prioritizing older age groups (Costa et al., 2022).

The strategy for allocating vaccines factored in population sizes, prioritized groups, the rolling average of mortality rates in various locations, and the imperative to preserve a workforce capable of sustaining healthcare and other vital services in line with the guidelines set forth by the National Immunization Program (PNI). This program underscored the commitment to vaccinate all demographic groups, albeit in phases, due to the limited availability of vaccine doses for immediate, widespread administration. The specifics of the distribution plan were articulated in technical reports and bulletins, with comprehensive details accessible via the Ministry of Health's website (Brazil, 2021).

3 METHODOLOGY

This study utilized data sourced from the Brazilian Institute of Geography and Statistics (IBGE), the Center for Strategic Information on Health Surveillance (CIEVS-RJ), the Health Secretary of the State of Rio de Janeiro (SES), the Mortality Information System (SIM), and the Ministry of Health. The dataset included estimates of the state's population for 2021, along with the number of confirmed infections, total deaths, and COVID-19-related deaths in each municipality of Rio de Janeiro, with updates current as of January 19, 2021.

Initially, data from all 92 municipalities in the state were collected. However, to mitigate potential distortions in the fatality rate per 100,000 inhabitants, 25 municipalities with populations under 20,000 were excluded from further analysis. For the remaining 67 municipalities, rates of cases and deaths per 100,000 inhabitants were calculated. These metrics informed potential scenarios for prioritizing vaccine distribution, aiming to maximize the number of life-years preserved across the state's population.

Table 1. Sample Data from Municipalities in the State of Rio de Janeiro.

Municipality	Population	Cases	Deaths	Cases/100K	Deaths/100K
Rio de Janeiro	6,775,561	248,184	20,479	3,662.93	302.25
São Gonçalo	1,098,357	42,197	1,896	3,841.835	172.62
Duque de Caxias	929,449	17,720	1,132	1,906.51	121.80
Nova Iguaçu	825,388	16,060	1,148	1,945.75	139.09
Niterói	516,981	36,164	1,519	6,995.23	293.83
Belford Roxo	515,239	19,369	501	3,759.23	97.3
Campos dos Goytacazes	514,643	21,283	918	4,135.49	178.4
São Joao de Meriti	473,385	7,688	768	1,624.05	162.3
Petrópolis	307,144	18,010	590	5,863.70	192.09
Volta Redonda	274,925	20,579	510	7,485.32	185.50

Source: Prepared by the authors.

To analyze the data, a dataset[1] was constructed with the attributes “Municipality,” “Cases,” “Deaths,” “Cases per 100,000 inhabitants”, and “Deaths per 100,000 inhabitants” and imported into R-Studio. Following normalization, a Pearson correlation matrix was generated to assess the linear relationship between the continuous variables.

Utilizing unsupervised machine learning algorithms, the within-cluster sum of squares (WSS), also known as the Elbow Method[2], was calculated to determine the optimal number of clusters by minimizing the sum of squared distances (Zumel & Mount, 2014). This facilitated the segmentation of municipalities into clusters that were relatively homogeneous with respect to the four aforementioned variables. Cluster analysis aims to organize data into groups or clusters based on similarity, with the premise that data points within a cluster are more similar to each other than to those in other clusters, according to a predetermined criterion (Lachi & Rocha, 2005).

To quantify the number of life years preserved, data on total deaths by age group for the two years preceding the onset of the COVID-19 pandemic in Rio de Janeiro (2018 and 2019) were collected, the average calculated, and the proportion of total deaths for each age group during the 320 days preceding the vaccine rollout was estimated.

$$Average\ of\ Overall\ Deaths = \frac{Overall\ Deaths\ 2018 + Overall\ Deaths\ 2019}{730\ days} x320\ days$$

Equation 1. Average Number of Overall Deaths. Source: Prepared by the authors.

$$Percentage\ of\ Overall\ Deaths = \frac{Average\ of\ Overall\ Deaths}{Population\ Estimate\ by\ Age} x100$$

Equation 2. Percentage of Overall Deaths. Source: Prepared by the authors.

This dataset allowed us to construct a “Years of Life” matrix, simulating life expectancy by age and projecting the current population’s lifespan. For each subsequent year, the estimated percentage of overall deaths for each age group was subtracted successively, up to 99 years.

This method aimed to replace a static life expectancy (based on the average) with a dynamic estimate that varies according to age. By summing up the projected populations by age for each subsequent year, we obtained the total estimated years of life for each age group.

$$\sum_{a=age}^{n=99} Population\ Estimate\ in\ Years - (Population\ Estimate * Overall\ Deaths)$$

Equation 3. Estimated Life Expectancy by Age. Source: Prepared by the authors.

After collecting data on deaths caused by COVID-19 distributed by age, their respective percentages were calculated.

$$Percentage\ of\ COVID-19\ Deaths = \frac{COVID-19\ Deaths}{Population\ Estimate} x100$$

Equation 4. Percentage of COVID-19 Deaths. Source: Prepared by the authors

Although Oliveira and colleagues (2020) assert that “CoronaVac is a vaccine containing inactivated virus, vaccines incorporating non-replicating viral vectors typically exhibit an efficacy rate of approximately 79%,” the scarcity of dedicated research on the efficacy of the CoronaVac vaccine led to estimations ranging from 80% to 95% efficacy in 27 scenarios across various age groups. An additional 54 scenarios were considered, with efficacy ranging from 5% to 10% in each age group starting from 60 years old, resulting in a total of 81 scenarios. These scenarios were used to distribute the available vaccines from the first batch among the ten (10) potential age groups.

The calculations were based on the percentage of COVID-19 deaths within each age group multiplied by the cumulative years that the population within that age group would be expected to live, as per the “Years of Life” matrix, while varying the efficacy levels across the indicated scenarios.

These calculations were conducted exclusively for the two clusters with the highest death tolls, aiming to determine the optimal choice of priority municipality or municipalities, with the objective of maximizing the

[1] “Dataset” refers to a compilation of typically organized data.
[2] The Elbow Method is employed to ascertain the most suitable number of clusters in k-means clustering (Ketchen et al., 1996).

variables related to the number of life-years saved.

One limitation identified in this study pertains to the use of data collected from the latest national census (IBGE, 2010), potentially resulting in inaccuracies in population estimates. Additionally, the dataset does not differentiate between deaths among individuals with comorbidities and general deaths.

Furthermore, this study is confined to analyzing municipalities within the state of Rio de Janeiro and formulating a vaccine management strategy solely for the first batch of vaccines, aligning with the study's focus on decision-making amidst resource constraints.

In this study, the age group of 0-4 years was excluded initially in accordance with the Ministry of Health's initial recommendation against administering the vaccine (Brazil, 2020). Age groups over 100 years old were also disregarded due to their minimal representation in terms of numbers. Moreover, considerations regarding professional activities and individuals with comorbidities were omitted due to challenges in obtaining accurate data from public databases.

Lastly, it is important to note that data from 25 municipalities in the state of Rio de Janeiro were excluded from the analysis due to their populations being under 20,000 inhabitants, which could potentially skew the lethality rate per 100,000 inhabitants.

4 RESULTS

Considering the variables outlined in the Methodology section, a Pearson Correlation matrix was generated to elucidate the data and confirm the relationships among the factors, as illustrated in Figure 1 below.

Figure 1. Pearson's correlation matrix. Source: Prepared by the authors.

From Figure 1, it is evident that the variables of Cases and Deaths exhibit a strong correlation, while Cases and Deaths per 100K display a positive correlation. Additionally, Cases per 100K show no significant correlation with Cases or Deaths, indicating a low level of interdependence with Deaths per 100K.

Following the assessment of the degree of correlation between each factor, the Elbow Method graph was constructed to determine the optimal number of clusters for the municipalities in the state of Rio de Janeiro.

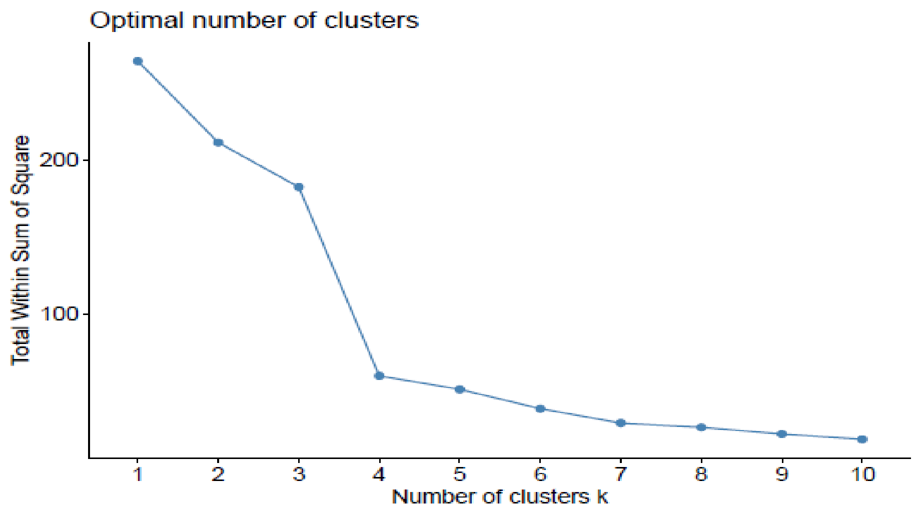

Chart 1. Elbow method. Source: Prepared by the authors.

The analysis of Chart 01 reveals that k=4 represents the balance between within-cluster homogeneity and within-cluster dissimilarity, identified as the point on the curve farthest from a line drawn between the first and last points.

Subsequently, K-means clustering with 4 clusters was performed, yielding centroids (the average of instances in each cluster), as depicted in Figure 2 of the Centroids below.

```
##   cluster       Cases      Deaths  Cases/100K Deaths/100K
## 1       1 -0.13597538 -0.09885335 -0.8146854  -0.3384693
## 2       2  7.75495568  7.97934525 -0.6433849   2.9637284
## 3       3 -0.11115640 -0.18591433  1.4481008  -1.3449022
## 4       4 -0.09632703 -0.13339625  0.6977555   0.6027841
```

Figure 2. Centroids. Source: Prepared by the authors.

Principal Component Analysis (PCA) was then conducted to transform the dataset from its original space to another, where the majority of the information is contained in the first coordinate, followed by subsequent coordinates (Ketchen et al., 1996). This allowed for the representation of the 4-dimensional dataset in a two-dimensional format, capturing the most significant coordinates. The resulting two-dimensional graph from PCA accounted for 83.8% (56.9% + 26.9%) of the distributed variance, as illustrated in graph 2 of the percentage of variance below.

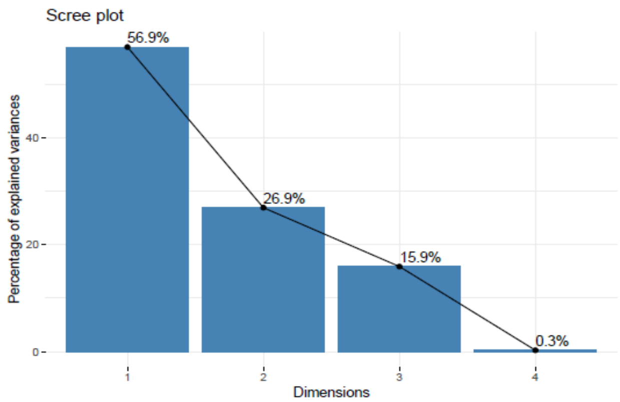

Chart 1. Percentage of Variance Explained in the Principal Components (PCA). Source: Prepared by the authors.

Based on the analyses conducted, which provided adequate justification for the selection of the number of clusters using K-means, clustering was performed, resulting in the following groupings:

Table 1. Clusters.

Cluster 01	Cluster 02	Cluster 03	Cluster 04
São Gonçalo	Rio de Janeiro	Macaé	Niterói
Duque de Caxias		Itaperuna	Petrópolis
Nova Iguaçu		Búzios	Volta Redonda
Belford Roxo		Cordeiro	Angra dos Reis
Campos dos Goytacazes		Silva Jardim	Nova Friburgo
São Joao de Meriti		Cantagalo	Teresópolis
Magé			Barra Mansa

Itaboraí			Maricá
Cabo Frio			Itaguaí
Mesquita			Resende
Nilópolis			Três Rios
Rio das Ostras			Guapimirim
Queimados			Rio Bonito
Araruama			Casimiro de Abreu
São Pedro da Aldeia			Paraíba do Sul
Japeri			Santo Antônio de Pádua
Barra do Pirai			São João da Barra
Saquarema			Tanguá
Seropédica			Pirai
Valença			Iguaba Grande
Cachoeiras de Macacu			Miracema
Paracambi			Pinheiral
Mangaratiba			Quissamã
Paraty			Conceição de Macabu
São Francisco de Itabapoana			Itaocara
São Fidelis			São Jose do Vale do Rio Preto
Bom Jesus do Itabapoana			Porto Real
Vassouras			
Itatiaia			
Arraial do Cabo			
Paty do Alferes			
Bom Jardim			
Miguel Pereira			

Source: Prepared by the authors.

It is imperative to visually inspect the proximity of the municipalities outlined in Table 2 to the clusters. These clusters are formed based on the concept of similarity, where the data points within a cluster are closer to its centroid than they are to the centroid of any other cluster. The findings are depicted in Chart 3:

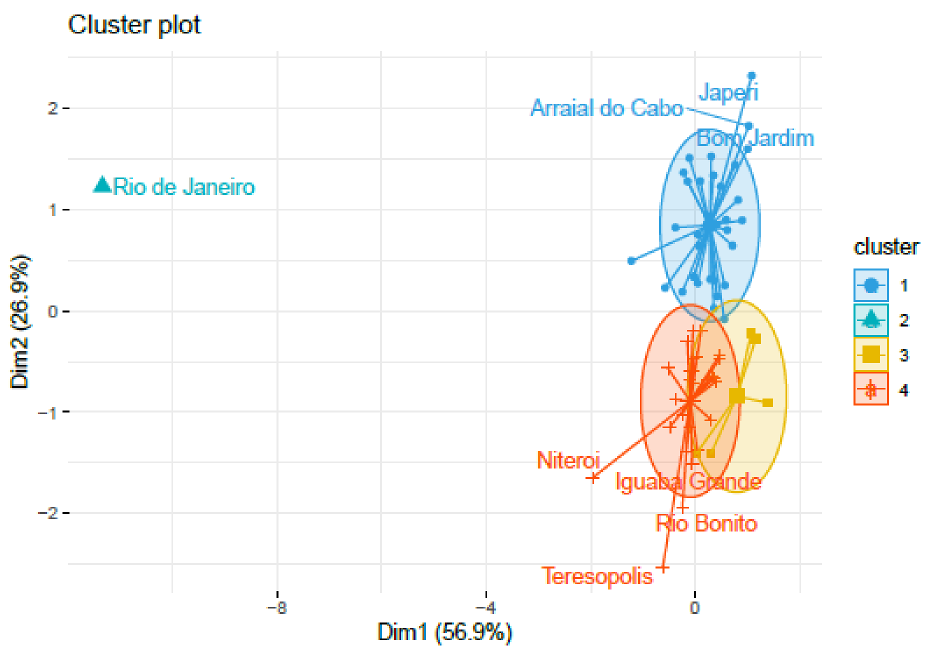

Chart 3. Cluster chart. Source: Prepared by the authors.

Given the data presented, clusters 2 and 4 have been singled out for further analysis due to their notably poor mortality indicators in the state of Rio de Janeiro.

4.1 Analysis of Cluster 2 – Municipality of Rio de Janeiro

In light of the proposition that the 488,320 vaccine doses would be exclusively allocated to the municipality of Rio de Janeiro, simulations were conducted to estimate the years saved.

Given that the available vaccine doses surpassed the population of a single age group, various scenarios were considered. In these scenarios, doses were initially administered to one age group, with any surplus then allocated to the subsequent age group as a priority. If no subsequent age group were available, the surplus would be distributed to the age group below, maintaining a sequential approach, as illustrated in the flowchart below:

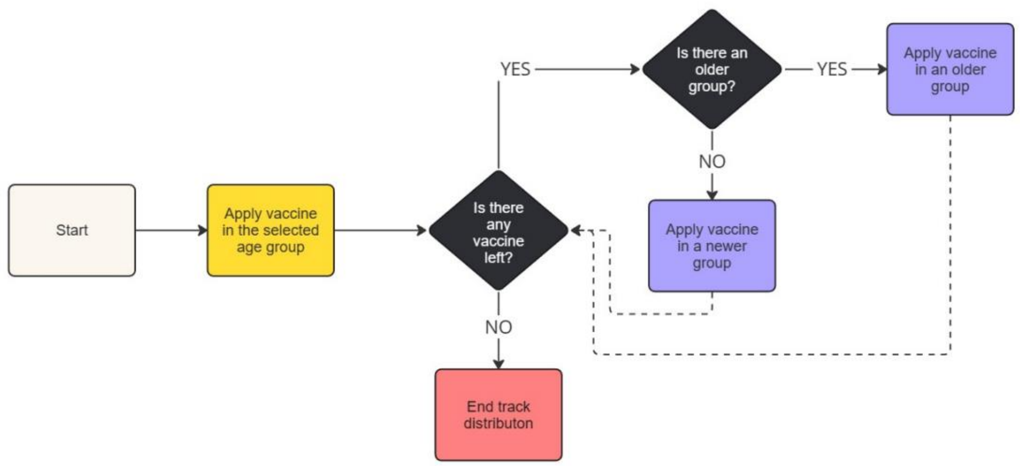

Figure 3. Flowchart. Source: Prepared by the authors.

Consequently, the most favorable outcomes were observed with the following distribution:

Table 03. Results of the Distribution by Age Group in the Municipality of Rio de Janeiro.

Age Group	Vaccines Administered
60 to 69 yo	34,144
70 to 79 yo	302,801
80 to 89 yo	131,637
90 yo and over	19,738

Source: Prepared by the authors.

The results favor the prioritization of older age groups to maximize the number of years of life saved, considering the vaccine's uniform efficacy rates of 80%, 90%, and 95%, as depicted in Chart 4 below:

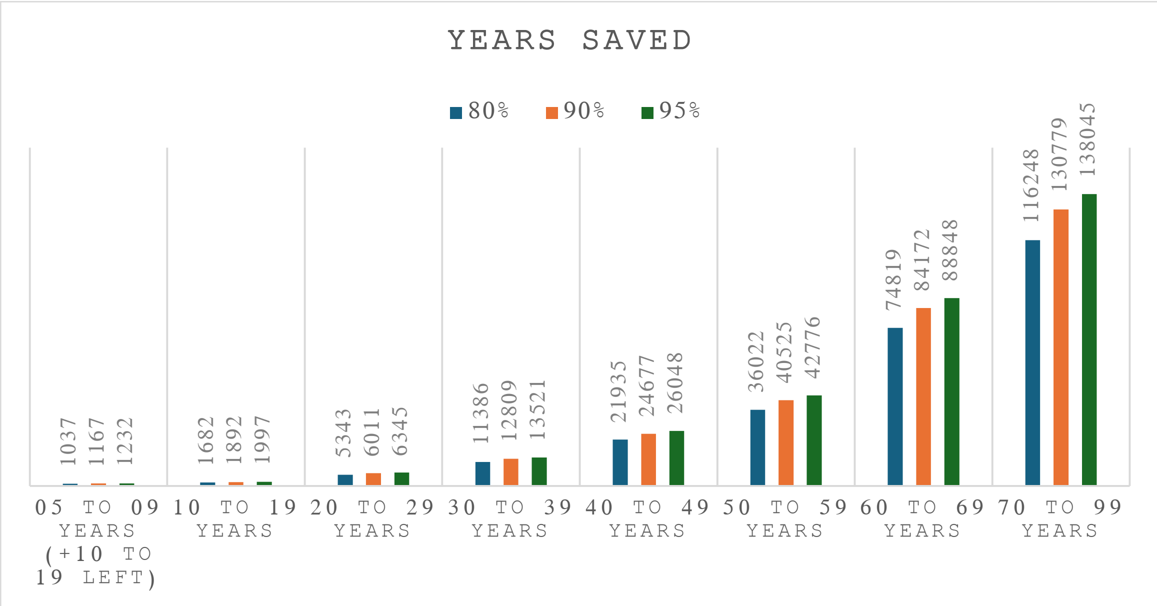

Chart 4. Projection of years of life saved (YLS) in the municipality of Rio de Janeiro. Source: Prepared by the authors.

4.2 Analysis of Cluster 4 – 27 municipalities in Rio de Janeiro

Given the allocation of 488,320 vaccine doses exclusively to the 27 municipalities in Cluster 4, simulations akin to those outlined in the methodology were conducted for the distribution within the municipality of Rio de Janeiro.

Since the number of doses surpassed the population of any single age group, the same distribution criteria employed for Cluster 2 were applied. Optimal outcomes were achieved with the following allocations:

Table 04. Results compiled from the distribution by age group in all 27 municipalities.

Age Group	Vaccines Administered
60 to 69 yo	256,107
70 to 79 yo	169,080
80 to 89 yo	56,396
90 yo and over	6,737

Source: Prepared by the authors.

In this cluster, it was observed that the number of elderly individuals aged over 90 was 34% lower compared to Cluster 2. Consequently, the reduced number of elderly individuals in the higher age brackets resulted in the distribution of vaccines reaching seven times as many people in the 60 to 69 age group.

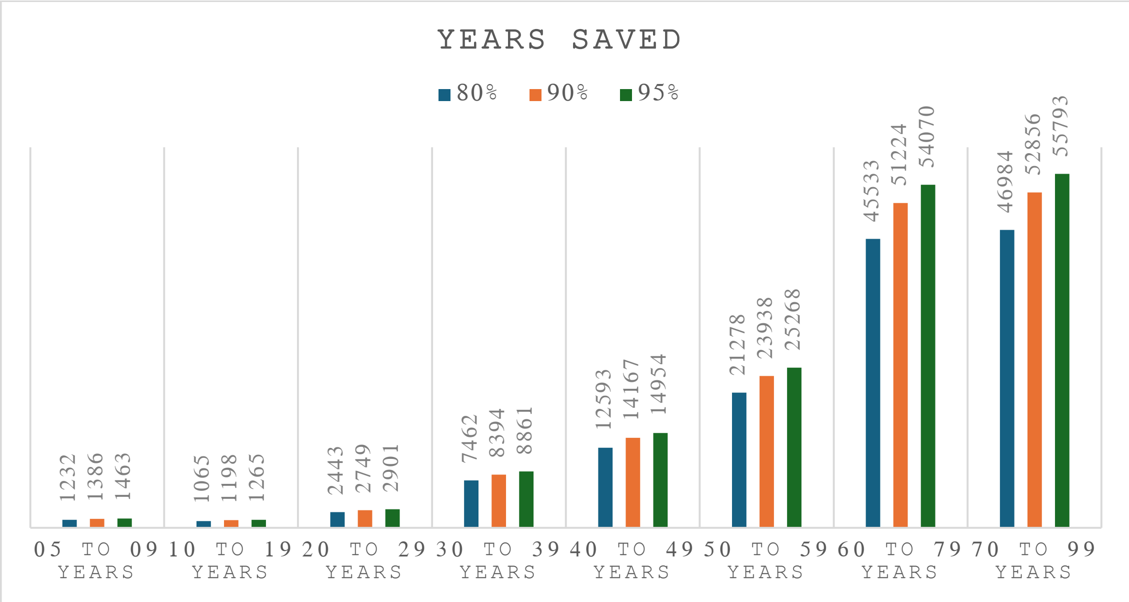

Chart 5. Projection of years of life saved (YLS) in 27 municipalities of the state of Rio de Janeiro. Source: Prepared by the authors.

The number of life years saved is less than half of the corresponding figure for Cluster 2 (the municipality of Rio de Janeiro) in both the optimistic and pessimistic scenarios.

4.3. Consolidated Results

Based on the findings derived from the vaccination distribution scenarios in Cluster 2 (the municipality of Rio de Janeiro), the entire state of Rio de Janeiro (comprising 92 municipalities), and Cluster 4 (27 municipalities), and in alignment with the Ministry of Health's recommendation of prioritizing vaccine distribution by decreasing age groups, the following observations can be made:

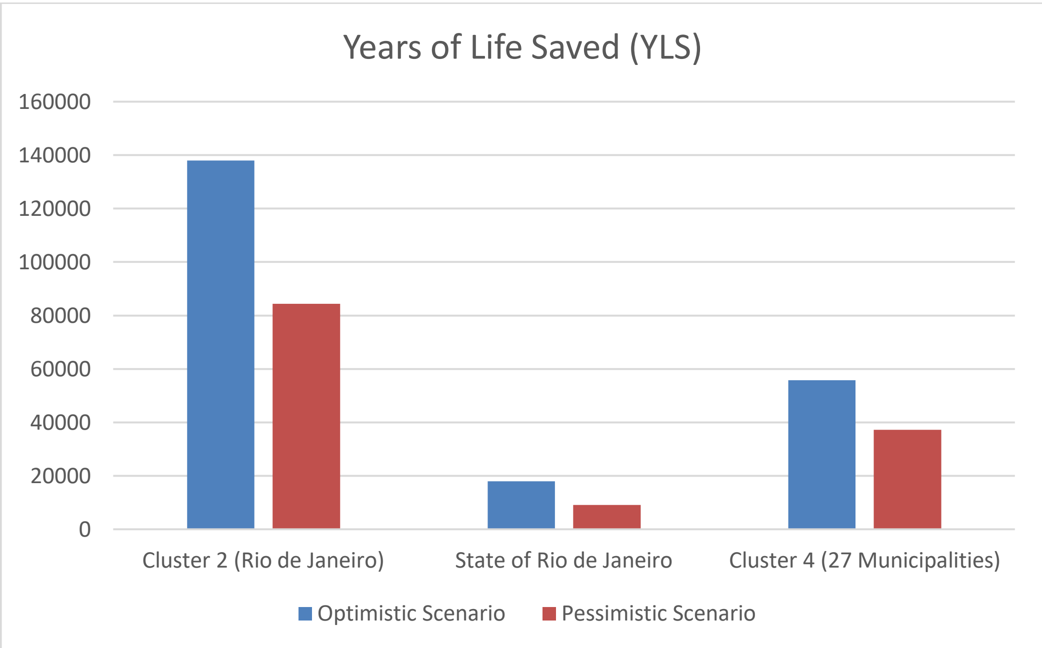

Chart 6. Vaccination distribution by years of life saved (YLS). Source: Prepared by the authors.

Clustering could potentially lead to an estimated increase of 669.27% (in the optimistic scenario). This indicates that if vaccines were allocated primarily to the municipality of Rio de Janeiro at the expense of others, the number of years saved among the population of Rio de Janeiro would be seven times higher compared to the distribution of vaccines across the entire state. This mathematical outcome is attributed to the concentrated vaccination in the 70-79 age group, which exhibits the highest potential for saving years. In comparison to Cluster 2, this increase amounts to 147.42%. In the pessimistic scenario, these figures shift to 824.18% and 126.67%, respectively.

5 FINAL REMARKS

This study aimed to furnish readers with data collected from the principal epidemiological observatories in the state of Rio de Janeiro at the onset of the COVID-19 pandemic. It also sought to scrutinize the challenges faced by public administration in the context of vaccine distribution. These insights facilitated the identification of strategic alternatives for combatting the disease and proposed scenarios for contemplation and decision-making support in Rio de Janeiro. This was achieved by considering municipalities that could potentially be prioritized for the initial supply of the first vaccine batch in the state, contingent upon the number of years saved.

Prioritizing elderly individuals in descending order of age for vaccination, particularly concentrating the first batch exclusively in the municipality of Rio de Janeiro, yielded results more than seven times higher in terms of the number of years saved compared to statewide distribution. This outcome also notably outperformed the concentration of doses in other clusters identified in this study.

Therefore, the findings underscore the efficacy of concentrating vaccine doses in the capital city of Rio de Janeiro. Additionally, it is imperative to acknowledge that results derived from quantitative data may elicit actions that could be deemed undemocratic or conflicting with political and social interests. For instance, favoring one municipality to appease a single mayor at the expense of 91 others, even with the aim of achieving more favorable outcomes, raises ethical and democratic considerations.

Future research endeavors could delve into assessing the quality of the years of life saved and evaluating the impact of this data on the overall life expectancy of the population. Such investigations could address pertinent economic, ethical, and philosophical questions.

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