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Logistical Performance of a COVID-19 Vaccination Campaign in a Decentralized Health System

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Abstract

Background/Objectives: The COVID-19 pandemic imposed logistical challenges on health systems, particularly for mass vaccination campaigns under emergency conditions. In decentralized health systems, the absence of a structured preparedness phase may compromise coordination, allocation, and operational performance. This study analyzes the vaccination campaign in a municipality in southern Brazil, examining how the overlap of the preparedness and response phases affected outcomes and how alternative logistical scenarios could have altered campaign performance. Methods: An empirical analysis was conducted using scenario-based simulation with stock and flow structures. The model represents vaccine procurement, distribution across national, state, regional, and municipal levels, and municipal vaccination capacity. Real data from the 2021 vaccination campaign in the municipality were used to build a Business-as-Usual scenario, compared with alternative scenarios involving changes in procurement predictability, allocation rules, and operational capacity. Results: Vaccination outcomes were strongly conditioned by upstream allocation decisions, particularly at the national state level. Isolated adjustments at intermediate supply chain levels produced limited improvements when upstream constraints persisted. Scenarios combining improved alignment between forecasted and acquired doses with operational capacity showed higher vaccination potential, revealing a gap between observed performance and system capacity. Conclusions: The findings reinforce that preparedness is a critical determinant of vaccination performance and must precede response in emergency contexts. Supply predictability alone is insufficient without coordinated allocation mechanisms and operational readiness across governance levels. This study provides empirical evidence on how preparation-related decisions shape vaccination outcomes in decentralized health systems and inform logistical coordination in future emergencies.

Keywords: humanitarian logistics; emergency vaccination; preparedness; vaccine distribution; decentralized governance

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1. Introduction

The COVID-19 pandemic, declared a Public Health Emergency of International Concern by the World Health Organization (WHO) in early 2020, represented one of the most severe global health crises of the 21st century and posed unprecedented logistical challenges for health systems worldwide. Beyond managing infection surges, governments

were required to rapidly organize large-scale vaccination campaigns under conditions of uncertainty, scarcity, and time pressure. Although equitable and timely vaccine distribution was widely recognized as essential to pandemic control, its implementation proved highly complex, demanding coordinated logistics across multiple governance levels. Cold chain requirements, infrastructure limitations, shortages of ancillary supplies, and unequal access to vaccines significantly constrained rollout efforts. These challenges were strongly intertwined with global inequities, as vaccine supply was initially concentrated in high-income countries: by late 2023, nearly 80% of individuals in these countries had received at least one dose, compared to approximately 33% in low-income countries [1] The strain on supporting inputs, such as syringes, further exposed vulnerabilities in global preparedness for mass immunization.

In Brazil, the vaccination campaign unfolded within a decentralized public health system in which vaccine procurement was centralized at the federal level, while distribution and administration were the responsibility of states and municipalities. This institutional arrangement amplified coordination challenges during the emergency. The National Plan for the Operationalization of COVID-19 Vaccination (PNO) faced difficulties in aligning vaccine supply with the heterogeneous operational capacities of thousands of municipalities, resulting in delays, uneven allocation of doses, and periodic shortages of critical resources. In the absence of a structured and autonomous preparedness phase, decision-making frequently assumes a reactive character. Empirical evidence from the Brazilian context illustrates these constraints. For example, mass drive-thru vaccination initiatives encountered supply shortfalls and operational bottlenecks, reflecting the consequences of limited planning [2] More broadly, the pandemic exposed longstanding fragilities in coordination and governance, even in a health system designed to operate in a decentralized manner [3].

Despite the centrality of logistics to vaccination performance, much of the existing research on COVID-19 responses has focused primarily on epidemiological outcomes and public health interventions, with comparatively limited attention to supply chain organization, allocation mechanisms, and operational capacity. Numerous modeling efforts were developed during the pandemic, but these largely emphasized disease transmission dynamics and intervention effects. A scoping review of COVID-19 models applied in Brazil during the first year of the pandemic identified a marked lack of attention to social and logistical inequalities [4]. This pattern reflects a broader tendency in pandemic preparedness research, where models often overlook supply chain constraints and governance arrangements that shape implementation outcomes [5]. As a result, relatively few studies have examined how the absence or weakening of a distinct preparedness phase affects the operational performance of emergency vaccination campaigns, particularly in decentralized health systems. This represents an important gap in the humanitarian logistics and emergency management literature [6,7].

This study addresses this gap by examining the logistical consequences of overlapping preparation and response during the COVID-19 vaccination campaign in the municipality of Maringá, in southern Brazil. Specifically, it investigates how constraints in vaccine procurement, allocation across governance levels, and municipal operational capacity shaped vaccination outcomes. Using an empirical case study and scenario-based simulation, the analysis examines how alternative procurement and distribution arrangements could have affected campaign performance. The modeling approach is employed as an analytical tool to compare scenarios and trace how upstream decisions propagate to the municipal level, rather than as an end.

The contribution of this research is threefold. First, it advances humanitarian logistics literature by providing empirical evidence on how preparation-related decisions condition response performance in a real-world emergency vaccination campaign. Second, it con-

tributes to discussions on equity and resilience in public health systems by demonstrating that proportional allocation and operational readiness are not only normative goals but also determinants of system effectiveness, aligning with global health objectives, such as the United Nations Sustainable Development Goals 3 and 10. Third, from a practical perspective, the findings offer insights for public managers and policymakers by identifying which logistical levers have the greatest influence on vaccination outcomes, thereby supporting more coherent planning in future health emergencies.

The remainder of this article is structured as follows. Section 2 reviews the theoretical background on humanitarian logistics, emergency vaccination, and preparedness and response phases. Section 3 presents the methodology, describing the case study context and the scenario-based simulation approach. Section 4 reports the results of the simulated scenarios, comparing observed outcomes with alternative configurations. Section 5 discusses the implications of these findings, considering existing literature. Finally, Section 6 concludes the article, outlining its main contributions, limitations, and directions for future research.

2. Theoretical Background

2.1. Humanitarian Logistics and Emergency Vaccination

According to Brazil's National Plan for the Operationalization of COVID-19 Vaccination, vaccine distribution relied on a combination of air and road transport, supported by a fleet of refrigerated vehicles equipped with satellite monitoring to ensure cold chain integrity [8]. Within the state of Paraná, municipalities retained autonomy to organize vaccination according to local dose availability and service capacity, reflecting the decentralized structure of Brazil's Unified Health System (SUS). While decentralization allows for local adaptation, it also increases coordination complexity, particularly during large-scale emergencies. During the initial stages of the COVID-19 vaccination campaign, limited federal guidance required subnational actors to assume leadership roles, often relying on ad hoc coordination mechanisms, cross-sector partnerships, and digital tools to bridge governance gaps [2,9]. This experience exposed the difficulty of aligning multiple administrative levels in the absence of prior coordination arrangements.

Humanitarian logistics is commonly defined as the planning, implementation, and control of the efficient flow and storage of goods, information, and services from origin to consumption under emergency conditions [10]. Within this field, the disaster management cycle provides a foundational conceptual framework, distinguishing preparedness from response and recovery phases. Empirical research consistently shows that investments in preparedness significantly enhance the speed, efficiency, and equity of emergency response operations. Pre-crisis planning, resource pre-positioning, and coordination protocols have been associated with higher beneficiary coverage and reduced operational bottlenecks [7]. Conversely, when preparedness is insufficient or overlaps with response activities, critical constraints tend to emerge, undermining operational performance and increasing losses [6].

Emergency vaccination campaigns introduce additional logistical challenges compared to other humanitarian operations. In addition to time pressure and uncertainty, vaccines require strict cold chain management and highly capillary distribution, reaching thousands of local health facilities rather than a limited number of centralized hubs. In Brazil, spatial analyses revealed that approximately 18% of the elderly population lived more than 4 km from the nearest vaccination site, indicating significant last-mile access barriers [8]. Regional disparities in infrastructure and service capacity further exacerbated these challenges. Although vaccines were procured centrally, the absence of coordinated preparation led to shortages of ancillary supplies, such as syringes, and uneven allocation of doses across municipalities, resulting in localized bottlenecks despite sufficient aggregate stock [2].

These dynamics illustrate how decentralized systems can become fragmented in the absence of structured preparedness mechanisms, reinforcing the need for proactive planning and coordination before crisis onset.

Recent studies have also emphasized the specific challenges of healthcare and vaccine supply chains in low- and middle-income countries, where decentralized governance structures, procurement volatility, and institutional asymmetries are common [11]. In such contexts, coordination across multiple administrative levels, infrastructure disparities, and uncertainty in supply flows tend to exacerbate distribution inefficiencies and inequities. Empirical evidence indicates that mismatches between procurement, allocation, and local operational capacity are recurrent issues, particularly during large-scale health emergencies [12]. In the Brazilian context, recent studies highlight that supply chain disruptions were accompanied by limited forecasting capacity, low technological adoption, and strong dependence on adaptive and collaborative mechanisms to sustain procurement processes under crisis conditions [13]. Additionally, prior disaster experience and risk perception do not necessarily translate into stronger institutional preparedness or coordinated response, especially in settings marked by governance fragmentation [14]. In parallel, the application of System Dynamics in humanitarian logistics has been increasingly explored to analyze allocation problems and material flows under uncertainty, supporting the understanding of feedback structures, resource constraints, and dynamic interactions in emergency supply chains [7,15]. These contributions reinforce the relevance of simulation-based approaches to decision-making in complex, resource-constrained environments.

2.2. Simulation Approaches to Logistical Complexity

Emergency vaccination campaigns are characterized by multiple interacting flows, resource constraints, and decision-making across governance levels, which makes analytical simplification challenging. In this context, simulation approaches have been increasingly adopted in humanitarian logistics to support the analysis of complex operational systems and to explore alternative scenarios under uncertainty [6,7]. Recent studies have highlighted the role of simulation-based and experimental approaches, including serious games, as tools to support learning, coordination, and decision-making in humanitarian logistics under uncertainty [16]. Among these approaches, System Dynamics (SD) has been widely used as a modeling technique to represent stock-and-flow structures, capacity constraints, and time-dependent interactions in disaster response operations.

SD is particularly suitable for analyzing how inventory levels, distribution rates, and information delays interact over time in emergency supply chains. Rather than producing point predictions, SD models are commonly used to compare scenarios and assess the relative effects of alternative policies or configurations. In humanitarian operations management, such scenario-based simulation has been recognized as a valuable tool for learning and policy testing under crisis conditions, especially when empirical experimentation is not feasible [6,7].

Previous studies have applied simulation methods to vaccination and health emergency contexts, demonstrating their potential to explore allocation strategies and capacity constraints. For example, [17] examined interactions between vaccination supply and non-pharmaceutical interventions, while [18] analyzed how different prioritization schemes influence health outcomes under constrained supply. Other works have incorporated behavioral elements, such as vaccine acceptance, into dynamic models [19]. While these studies differ in scope and objectives, they collectively indicate that simulation can reveal how upstream decisions propagate through health systems and affect downstream performance. In the present study, SD is employed as an analytical framework to examine

logistical relationships and scenario outcomes, without explicitly modeling epidemiological dynamics or individual behavior.

2.3. Research Gap and Empirical Focus

Humanitarian supply chains are often characterized as complex systems, in which interdependence across multiple governance levels generates nonlinear effects and amplifies upstream disruptions. In such contexts, simulation-based approaches are particularly useful for exploring system behavior and decision trade-offs rather than producing precise forecasts [20].

Despite advances in modeling and simulation for health emergencies, relatively few studies have explicitly examined the logistics of mass vaccination in decentralized health systems or how the absence of a distinct preparedness phase affects operational performance. A recent review of humanitarian operations and SD highlighted the need for greater attention to the dynamic linkages between preparedness and response activities [6]. Similarly, reviews of outbreak response modeling emphasize that logistical implementation challenges remain underexplored compared to epidemiological dynamics [21].

This study addresses the gap by examining the logistical consequences of overlapping preparation and response during the COVID-19 vaccination campaign in a Brazilian municipality. Although previous studies have examined national vaccine logistics and procurement dynamics, limited attention has been given to how allocation distortions across federal levels (federal–state–municipal) propagate through decentralized systems and affect vaccination performance at the final node of the chain, particularly in medium-sized cities. This gap is especially relevant in federative contexts where allocation rules and transport capacities differ across governance levels. Using an empirical case study and scenario-based simulation grounded in System Dynamics, this study models how such allocation distortions cascade downstream, examining how constraints in vaccine procurement, intergovernmental allocation, and municipal operational capacity shaped vaccination outcomes. Prior research suggests that early delays and coordination failures can have disproportionate impacts on emergency performance, particularly during the initial stages of response [22] In line with this perspective, the present analysis examines how early procurement and distribution constraints influenced cumulative vaccination coverage.

The empirical design captures the entire vaccine supply chain at the federal, state, regional, and municipal levels in a typical Brazilian state, in logistical terms. Rather than isolating the local node, the analysis traces how national procurement decisions and state-level allocation mechanisms propagate through the distribution network and materialize at the point of service delivery. This multi-level perspective enables a detailed examination of cascading effects within a decentralized federative system. By integrating humanitarian logistics theory, the disaster management cycle, and scenario-based simulation, the study provides insights into how insufficient preparedness and allocation distortions across governance levels can undermine the performance of emergency vaccination. These insights contribute to the literature by linking preparation-related decisions to observed operational outcomes and by highlighting the importance of coordinated planning across governance levels for future public health emergencies [6,7,21].

3. Materials and Methods

This research adopts a case study design to analyze the emergency process of vaccination against COVID-19 in a municipality in southern Brazil, to understand the complexity of humanitarian logistics operations in a crisis, where multiple actors interact in conditions of uncertainty and urgency. Our post-event analysis seeks to understand how the flows of internal distribution of vaccines took place throughout the crisis, until they reached the

municipal level. To analyze the interconnected dynamics of the vaccine supply chain, we employ Systems Dynamics modeling and simulation. Systems Dynamics was chosen for its ability to represent stock and flow relationships over time [15]. This modeling approach is aligned with disaster risk reduction frameworks, enabling the simulation of preparedness and response scenarios to anticipate system vulnerabilities and improve resilience.

The logistical process of distribution and vaccination in the Brazilian case did not start autonomously. This is because, given the complexity of the global crisis, an agreement was established by which all countries received available doses. There was a forecast for how many doses each country would receive. However, these values were not always confirmed at the time of reception. As the vaccines arrived in Brazil, they were distributed to the states. The states distributed these doses among their health regions and then to the municipalities. As more doses flow through these levels, municipal reception increases, expanding the number of doses available for administration.

Because it is a product that needs a cold transport chain, as the reception of vaccines at the national, state, and regional levels increases, transport restrictions become more pronounced. These capacity limits can decrease the state and regional flow rate, which reduces municipal reception and moderates the availability of doses for administration. This mechanism gradually neutralizes the dynamics of strengthening procurement and distribution, stabilizing the system when transport capacity becomes saturated. The municipalities also depended on operational capacity, which involves the demand for supplies and inputs, without these human resources and/or physical resources for the application of vaccines. Also, losses are likely to occur, related to the limits of handling, storage, or transportation.

By incorporating these elements into the inventory and flow structure, the model captures how systemic delays, input mismatches, and capacity constraints propagate along the vaccination chain, shaping the overall effectiveness of the emergency campaign. The modeling process began with the development of a base scenario, which reflects real vaccination data using the Coronavac and Pfizer vaccines in 2021. The state of Paraná is divided into 22 health regions, and the municipality belongs to the 15th Health Region, which covers 30 municipalities. Each municipality had the autonomy to organize its local vaccination plan, initially aimed at health professionals and the elderly, before expanding to younger age groups and individuals with comorbidities. Figure 1 represents the reference model of the vaccination process.

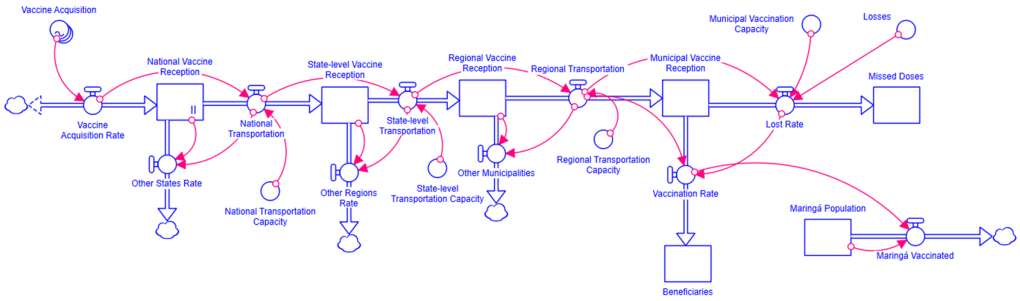


Figure 1. Stock and flux model.

We limited our model to understand the distribution from the national level to the municipality. We only considered the Coronavac and Pfizer vaccines, and in the vaccination schedule, only the first dose. Since our objective is to understand at the municipal level how the logistics chain behaved and to draw lessons from this case, we do not detail how the distribution occurred in other places (states, regionals or other municipalities). The Table 1 details the variables considered in the model.

Table 1. Model variables and definitions.

Name	Unit	Description
Vaccine Procurement	Doses	Variable that expresses the doses (Coronavac and Pfizer) sent by the consortium to Brazil
Vaccine Procurement Rate	Doses/month	National receipt rate of vaccine doses
National Vaccine Reception	Doses	Monthly stock of doses received in Brazil
National Transportation Capacity	Rate %	The percentage rate of vaccines that were sent to the state of Paraná
National Transportation	Doses/month	Number of doses sent per month to the state of Paraná
Other States Rate	Doses/month	Number of doses sent per month to the other states of the federation
State-level Vaccine Reception	Servings	Monthly stock of doses received in Paraná
State-level Transportation Capacity	Rate %	The percentage rate of vaccines that were sent to the 15 Regional Health Regions of Paraná
State-level Transportation	Doses/month	Number of doses sent per month to the 15 Regional Health of Paraná
Other Regions Rate	Doses/month	Number of doses sent per month to the other Health Regions of Paraná
Regional Vaccine Reception	Servings	Monthly stock of doses received at the 15 Regional Health Regions of Paraná
Regional Transportation Capacity	Rate %	The percentage rate of vaccines that were sent to the municipality
Regional Transportation	Doses/month	Number of doses sent per month to the municipality
Municipal Vaccination Capacity	Adimensional	Operational capacity of the municipality to carry out vaccination
Losses	Rate %	Percentage of trivial losses from the vaccination process
Lost Rate	Doses/month	Number of doses lost per month, due to trivial losses of the vaccination process and/or system incapacities
Missed Doses	Servings	Cumulative number of missed doses
Vaccination Rate	Doses/month	Number of doses effectively applied per month in the population of the municipality
Beneficiaries	Servings	Accumulated number of doses effectively applied to the population of the municipality
The municipality Population	People	Total number of people eligible for vaccination in the municipality
The municipality vaccinated population	Servings*People	Total number of people vaccinated in the municipality

The model was parameterized using quantitative data obtained from public databases, including the Ministry of Health's OpenDataSUS platform (Ministry of Health 2021a, 2021b, 2021c, 2021d), the daily epidemiological bulletins of the Paraná Health Department, and the Health Observatory of the Municipality [23]. These sources provided weekly time-series data for key variables during the 2021 campaign, including vaccine arrivals, distribution flows to the 15th Health Region, and records from municipal administrations of the Coronavac and Pfizer vaccines.

The purchased vaccines enter the Brazilian stock and are later distributed to the state of Paraná, limited by the National Transportation Capacity. From there, the doses go to the 15th Regional Health Secretariat, regulated by the State-level Transportation Capacity, and finally to the municipal level, where the Regional Transportation Capacity defines the portion of doses allocated to the municipality.

At the municipal level, effective immunization requires not only the availability of vaccines but also the presence of essential inputs (syringes, needles, and protective equipment), represented in the model by Vaccination Capacity. When these inputs are available, vaccines flow through the Vaccination Rate, increasing the stock of Beneficiaries—the cumulative number of vaccinated individuals. Losses can occur due to operational bottlenecks, storage limits, or insufficient inputs, partially mitigated by Reuse mechanisms that return materials to the system.

The stocks that represent the number of vaccines received per month in each link of the distribution chain start the simulation at zero. From then on, the vaccines received at the national level began to be distributed through the logistics flows. The distribution to the state of Paraná is based on Equation (1). All other logistics flows are expressed following the same logic. Finally, the stock of Missed Doses and the stock of Beneficiaries are due to the monthly accumulation of the Lost Rate and Vaccination Rate, respectively, expressed by Equations (2) and Equation (3).

$$\text{National Transportation} = \text{National Transportation Capacity} \times \text{Vaccine Procurement Rate} \quad (1)$$

$$\text{Lost Rate} = \text{Regional Transportation} \times \text{Municipal Vaccination Capacity} - (\text{Losses} \times \text{Regional Transportation}) \quad (2)$$

$$\text{Vacinnation Rate} = \text{Regional Transportation} - \text{Lost Rate} \quad (3)$$

To structure this assessment more systematically, the components of the stock-and-flow model were conceptually mapped in the preparedness and response phases of humanitarian logistics. In the Preparation Phase, demand is forecast using epidemiological and demographic data, supporting vaccine orders, procurements, and upstream allocation. The distribution to the state, regional, and municipal levels represents the continuation of this phase, aiming to ensure the conditions for maintaining the integrity of the vaccine.

In the Response Phase, vaccines and supplies are mobilized for administration by local health teams. The vaccination rate then depends on operational capacity and the availability of inputs, while inefficiencies can lead to missed doses. The final point of the process is the vaccinated population, which closes the cycle started during the demand forecast. Figure 2 shows the reading of the model from the Preparedness and Response phases of humanitarian logistics, with the elements in green associated with preparedness and the elements in blue with response.

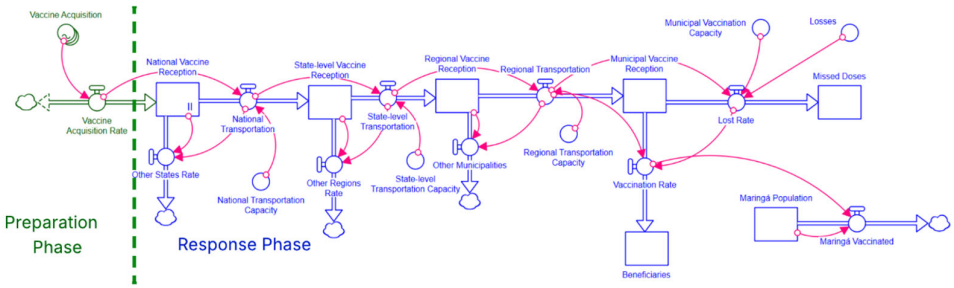


Figure 2. Stock and flux model across preparedness and response phases.

The model was built and simulated using the Stella Architect® Software (version 1.9.1, isee systems, inc., Lebanon, NH, USA), allowing the comparative evaluation of different scenarios. To validate the structure and underlying assumptions of the model, we conducted a semi-structured focus group with key professionals from the Paraná Department of Health, whose expert input was crucial to validate the realistic rates in distribution and identify critical bottlenecks in the management of the vaccination process, which were the basis of the scenario analysis.

3.1. Model Validation

The reference scenario, called Business-as-Usual (BAU), was developed through a participatory modeling approach involving two focus group sessions with professionals from the Paraná State Health Department and experts involved in the COVID-19 vaccination campaign. Empirical data were obtained from official reports, operational records (e.g., vaccine procurement and distribution records, inventory data, input availability records, and dose loss tracking), as well as qualitative reports provided by professionals in the field on logistical challenges, resource constraints, and vaccine handling and storage procedures. These sources were triangulated to support the quantification of the model parameters and the validation of systemic behaviors under real operating conditions. The BAU scenario reflects the actual operational dynamics of the municipality's vaccination process in 2021 and serves as a base model for evaluating alternative logistical and planning interventions. The Vaccine Procurement values considered in the model reflect the total vaccines that the country received each month of the study period, as shown in Table 2.

Table 2. Monthly national vaccine procurement.

Month	Coronavac/Butantan	BioNTech/PFIZER—1st Dose (D1)	Total
January	8,702,348	0	8,702,348
February	6,210,453	0	6,210,453
March	22,758,970	0	22,758,970
April	5,800,000	1,000,350	6,800,350
May	5,118,010	2,515,500	7,633,510
June	5,000,000	11,908,260	16,908,260
July	10,654,000	13,619,970	24,273,970
August	30,000,020	27,404,910	57,404,930
September	11,032,452	41,206,230	52,238,682
October	9,300,000	28,522,260	37,822,260
November	0	33,798,960	33,798,960
December	0	27,567,540	27,567,540

The initial stock of the model is represented by the National Vaccine Reception, which then feeds the remaining stocks from the transport capacities at each stage of distribution. From the collected data and triangulation with experts, the values associated with these transport capacities for each link of the distribution system were identified. These values are presented in Table 3.

Table 3. Transportation capacity parameters.

National Transportation Capacity	State-Level Transportation Capacity	Regional Transportation Capacity
2%	8.0%	50.0%

For the BAU scenario, an average monthly loss of 5% was identified when comparing the doses received by the municipality with the actual number of vaccinations performed. Thus, a Vaccination Capacity of 100% was adopted for modeling purposes, while the observed losses were represented by a fixed rate of 5%. These losses aggregate different potential sources, such as handling errors, input limitations (e.g., syringes and needles),

and local operational constraints, being treated as an exogenous variable to the model, without explicit details of the supply chain of these resources.

To ensure the reliability of the model, a multi-step validation process was carried out, combining structural verification, dimensional consistency verifications and behavioral validation through extreme conditions tests, following established standards for system dynamics modeling [24].

Structural validation focused on confirming that the causal relationships and feedback loops embedded in the inventory and flow model were consistent with the processes identified during the participatory phase. This involved verifying whether each flow influencing vaccine stocks at the federal, state, regional, and municipal levels was associated with a coherent equilibrium or booster feedback mechanism. For example, the loss flow was validated when, by increasing the Losses, the Missed Dosses stock increased proportionally to the reduction in the Beneficiaries stock for the period considered.

Dimensional consistency was checked using the unit verification tool available in the modeling software. Each variable was assigned coherent physical units (e.g., doses, months, or dimensionless fractions), and all equations were evaluated to ensure compatibility between stocks, flows, and ancillary variables. The unit verification procedure did not return dimensional inconsistencies, confirming the mathematical soundness of the model.

Then, extreme conditions tests were applied to assess whether the model behaved logically under unlikely boundary conditions. Three main tests were conducted:

1. Zero Procurement Scenario: When Vaccine Procurement was set to zero, vaccine stocks at all levels (federal, state, regional, and municipal) also remained zero. This behavior aligned with real-world expectations and demonstrated that the model correctly simulates a complete disruption in vaccine supply.
2. Scenario of Absence of Transport Capacity: When the Transport Capacity between the federal-state, state-regional, and regional-municipal levels was reduced to zero, vaccines continued to be "available" at the national level in the model, but no doses were transferred to subsequent levels due to the absence of logistical movement. As a result, municipal vaccination has been halted, and dose losses have increased at previous levels, where storage limits have been exceeded. This behavior reflects the practical consequence of logistical paralysis in vaccination campaigns: distribution collapses, and losses increase when doses cannot be transported through the cold chain.
3. Unlimited Capacity Scenario: When Transport, Handling, and Vaccination capacities were set to extremely high values (ten times the baseline), the system reflected that all vaccines arriving in the system were quickly transferred and administered, confirming that the model responds appropriately when logistical constraints are removed.

These tests under extreme conditions provided essential behavioral validation. In all cases, the model's responses were plausible, consistent in terms of direction, and aligned with stakeholder expectations. The results confirmed that the feedback structure behaves coherently in both scarcity and abundance situations, reproducing patterns typical of real emergency vaccination logistics, such as accumulation and loss of doses during bottlenecks, and efficient and large-scale administration when capacity is abundant.

We also validated the model by comparing the results of the BAU scenario with the actual values observed in the system under study from public data made available, from the national receipts. The Figure 3 presents the comparison between simulated and real vaccine flows at different territorial levels. Panels (a), (b), (c), and (d) show, respectively, the national, state, regional, and municipal vaccine receipt, contrasting simulated and observed data over time. The municipal panel also represents the number of vaccines effectively administered in the municipality under both real and simulated scenarios.



Figure 3. Observed and simulated monthly vaccine procurement.

The graphs show differences between the actual values and the simulated values over the months, especially in peak periods. This behavior stems from the model design itself, which uses constant average transport and distribution capacities over the simulated period. Consequently, the simulation tends to smooth out the monthly variations, not accurately reproducing the extreme values observed empirically in specific months. This limitation mainly affects the representation of abrupt peaks in receipt and redistribution but does not compromise the adherence of the model to the annual accumulated, which presents a good fit between simulated and actual values, as show in Figure 4.

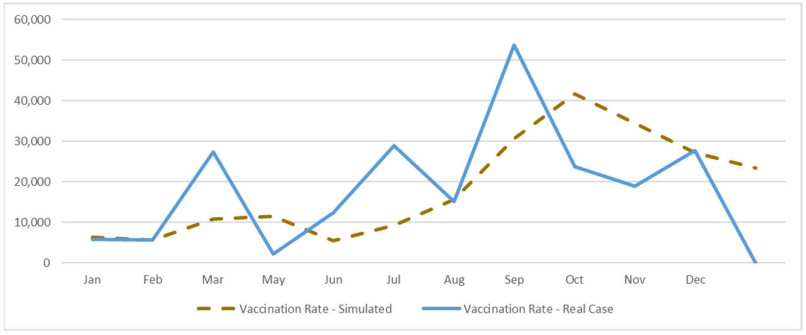


Figure 4. Vaccination in the municipality: simulated and real.

The municipal vaccination graph shows differences between the simulated and observed monthly values, especially during application peaks. This behavior is consistent with the use of average parameters in the model, which tends to smooth out monthly fluctuations and not fully reproduce extreme values, as in the previous figures. Even so, in the annual accumulation, the model shows a good fit. While the actual number of vaccinated people in the municipality in 2021 was 221,528, the model simulated 221,983, corresponding to an error of less than 2%. Considering that the eligible population over 18 years of age was 338,012, the aggregate performance indicates consistency of the model for comparative and scenario analyses, despite limitations in representing monthly variations.

3.2. Formulation Scenarios

Based on the reference scenario, we delineated a base case that reproduces the observed dynamics of the Brazilian COVID-19 vaccination supply chain (BAU). In addition,

we developed a second baseline (BAU Forecast) that preserves the same structure and operational assumptions of the BAU but replaces the realized national vaccine inflow with a forecast-based inflow. In practical terms, BAU Forecast represents a counterfactual in which Brazil, even under a centralized procurement arrangement, would have translated its national demand estimates into timely acquisitions consistent with the quantities projected as necessary, thereby reducing the upstream supply gap while keeping downstream distribution rules unchanged. Together, BAU and BAU Forecast provide the benchmark against which alternative changes in distribution and service capacity are assessed.

Vaccine procurement by the Federal Government is the first upstream process in the Brazilian vaccination system, because the quantities purchased determine the volumes available for allocation to the 26 states and the Federal District, typically using population-based criteria. [25] notes that COVID-19 vaccine distribution relied on pre-existing processes, networks, and partnerships to ensure availability while preserving product integrity, and highlights that, since launch, demand has persistently exceeded supply. This mismatch motivates the inclusion of BAU Forecast: even when acquisition is coordinated at the federal level, national demand estimates and monthly projections are produced and communicated to responsible entities, so examining a forecast-aligned procurement stream helps isolate how upstream adequacy interacts with downstream constraints.

After establishing these two baselines, we specified four alternative scenarios (A to D) that follow the order of the results and differ in the logistic capacities of specific links and in the service capacity for vaccine administration. Scenario A modifies the national to state allocation by imposing a population proportional rule at the federal to state link. Based on official population shares, the state of Paraná represents approximately 6% of Brazil's population, whereas the observed mean share of vaccines allocated to Paraná during the study period was about 2% in the BAU. Scenario A, therefore, assumes that, for the same national inflow, Paraná would receive 6% rather than 2%, while all downstream proportions remain as in the BAU.

Scenario B preserves the observed mean national to state allocation (that is, the BAU share received by Paraná) but adjusts the state to regional allocation according to population proportionality. In the BAU, the 15th Health Region received, on average, about 8% of the doses distributed to Paraná, whereas the proportional share implied by the population of the 15th Region relative to Paraná is approximately 7.5%. Scenario B, therefore, replaces the observed state-to-region percentage with the proportional value, while keeping the remaining downstream parameters unchanged.

Scenario C maintains the BAU proportions at the national to state and state to regional links but modifies the regional to municipal distribution within the 15th Health Region. In the observed case, Maringá received about 50% of the doses allocated to the 15th Region, while its population share in relation to the total population of the 15th Region is approximately 52%. Scenario C, therefore, adjusts the regional to municipality allocation from 50% to 52%, with all other parameters remaining consistent with the BAU.

Scenario D shifts the focus from distribution shares to the final service capacity of vaccine administration, capturing shortages of critical inputs and operational resources required for application. Under the base case, vaccination capacity is represented as 100%, consistent with a situation in which staffing, syringes, needles, and supporting supplies are sufficient to administer the doses available. Scenario D imposes a reduction in vaccination capacity from 100% to 50%, implying that even when doses are available in inventory, only half of the potential daily throughput can be realized, leading to stock accumulation and delayed administration until capacity is restored.

Finally, we propose an idealized scenario (Scenario E) that integrates proportional allocation across the entire distribution chain, from national to state, state to region, and region

to municipality, simultaneously applying the population proportional shares described in Scenarios A, B, and C. In Scenario E, unlike Scenario D, vaccination capacity is maintained at 100%, so the scenario represents an "ideal" logistics configuration in which upstream allocation and downstream redistribution are consistent with population shares and the service node is not constrained by input shortages. We also include a variation of this idealized configuration (Scenario E Forecast), which combines the population-proportion distribution rules of Scenario E with the forecast-based national inflow used in the BAU Forecast, allowing the analysis to separate improvements attributable to procurement adequacy from those attributable to equitable and efficient distribution.

Together, these simulations enable a structured assessment of how changes in transport and allocation rules across levels of the network, as well as variations in vaccination capacity driven by resource and input availability, influence vaccination performance under emergency conditions. The set of scenarios and their parameter changes are summarized in Table 4.

Table 4. Scenarios Identification.

Scenario	Description
BAU	Real vaccination campaign. Vaccine procurement follows actual consortium deliveries; Paraná receives ~2% of the national supply. Downstream regional and municipal distributions follow observed proportions. Vaccination capacity at 100%.
BAU Forecast	Same structure as BAU, but national vaccine inflow follows monthly forecasted quantities rather than actual consortium deliveries, isolating the effect of supply predictability.
Scenario A	Adjusted federal state allocation. Paraná receives a population proportional share (~6%) of national vaccines. Regional and municipal distributions unchanged.
Scenario B	Adjusted federal to state and state to regional allocation based on population shares. Municipal vaccination capacity unchanged.
Scenario C	Same allocation as Scenario B, with reduced municipal vaccination capacity (50%) due to input limitations, simulating stockpiling.
Scenario D	Combined scenario with adjusted allocations (as in Scenario B) and reduced vaccination capacity (50%).
Scenario E	Idealized scenario with population proportional allocation at all distribution levels (national, state, regional, and municipal) and unconstrained transport and vaccination capacities.
Scenario E Forecast	Same idealized configuration as Scenario E, but national vaccine inflow is based on forecasted quantities disclosed by the Federal Government rather than actual consortium deliveries.

The analysis of the results considered the theoretical framework, in particular, the relationship between the preparation and response phases in humanitarian logistics. The methodological design made it possible to identify the logistical impacts of carrying out both phases simultaneously, as occurred during the COVID-19 emergency campaign, and to propose improvements for future public health interventions.

4. Results

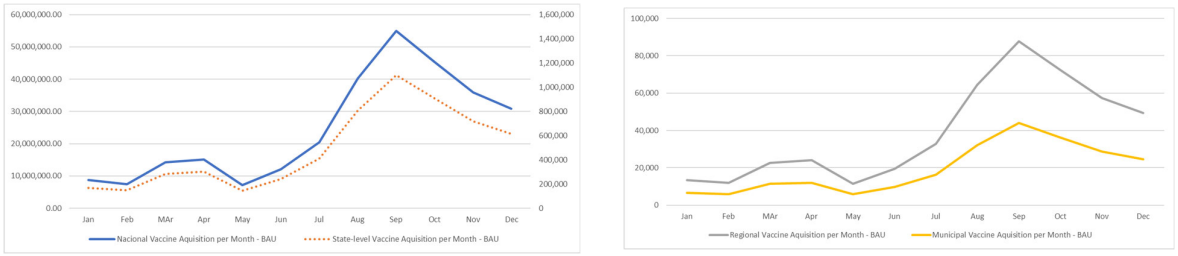
This section presents the results of the simulation of the COVID-19 vaccination campaign in a municipality in southern Brazil, during 2021. First, the BAU scenario is described, reflecting the actual historical data. This baseline is then compared with a forecast-based scenario, in which the same distribution structure observed in practice is maintained,

but vaccine procurement follows the quantities originally forecasted as necessary. This comparison allows isolating the effect of supply predictability on vaccination outcomes. Subsequently, the results of the proposed scenarios (A–E), which modify key logistical parameters, are presented, followed by a comparative analysis across scenarios.

4.1. Scenario BAU

The BAU scenario represents the observed dynamics of the COVID-19 vaccination campaign in the municipality in 2021 and serves as the baseline for comparison with alternative scenarios. The model reproduces vaccine procurement and distribution across national, state, regional, and municipal levels based on official data for CoronaVac and Pfizer.

Figure 5 presents BAU results for vaccine receipts across territorial levels. Panel (a) shows monthly receipts at the national and state levels, while panel (b) depicts the corresponding receipts at the regional and municipal levels. At the national level, inflows exhibit marked variability throughout the year, with sharp increases between August and September followed by a decline in the last quarter. Allocation to the state of Paraná remains consistently low relative to national volumes, reflecting an average share of approximately 2% during the campaign. Despite differences in scale, temporal behavior is coordinated across levels, indicating that fluctuations at the national level propagate downstream and shape availability at regional and municipal nodes.



(**a**) (**b**)

Figure 5. Vaccine receipts across levels.

Figure 6 reports the accumulated number of vaccinated individuals (beneficiaries) and accumulated missed doses over the year. Vaccination increases gradually in the first half of 2021 and accelerates from August onward, coinciding with higher upstream availability. By year's end, the BAU simulation reaches 221,983 vaccinated individuals in the municipality, closely matching the observed total of 221,528, indicating adequate aggregate fit. Missed doses accumulate at a lower rate, consistent with the assumed average loss rate of 5% embedded in the BAU configuration. Considering the municipal population of 371,406 inhabitants, these results suggest that coverage remained below the system's potential, particularly due to early supply constraints and the absence of a structured preparation phase.

Figure 7 compares BAU receipts with the BAU Forecast configuration across the supply chain. At the national (Figure 7a) and state (Figure 7b) levels, forecast-based procurement smooths the receipt profile by moderating peaks and troughs. This effect becomes more pronounced downstream at the regional level (Figure 7c, 15th Health Region) and at the municipal level (Figure 7d), where inflows display the most stable trajectory. Figure 8 shows that, despite smoother receipts, monthly vaccination rates do not necessarily increase under the BAU Forecast, suggesting that improved upstream predictability alone is insufficient when downstream allocation and distribution rules remain unchanged.

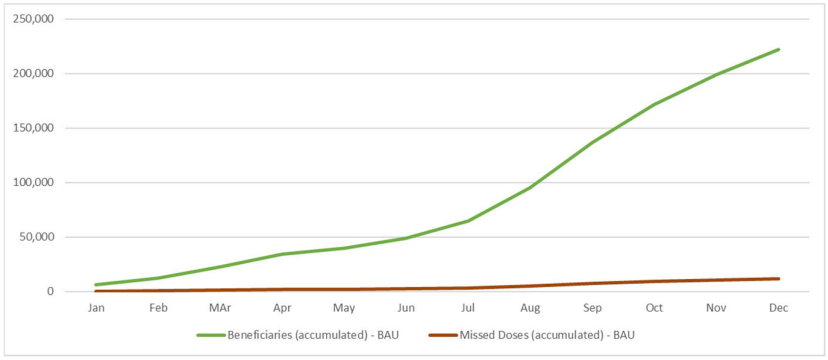


Figure 6. Vaccinated individuals and losses.

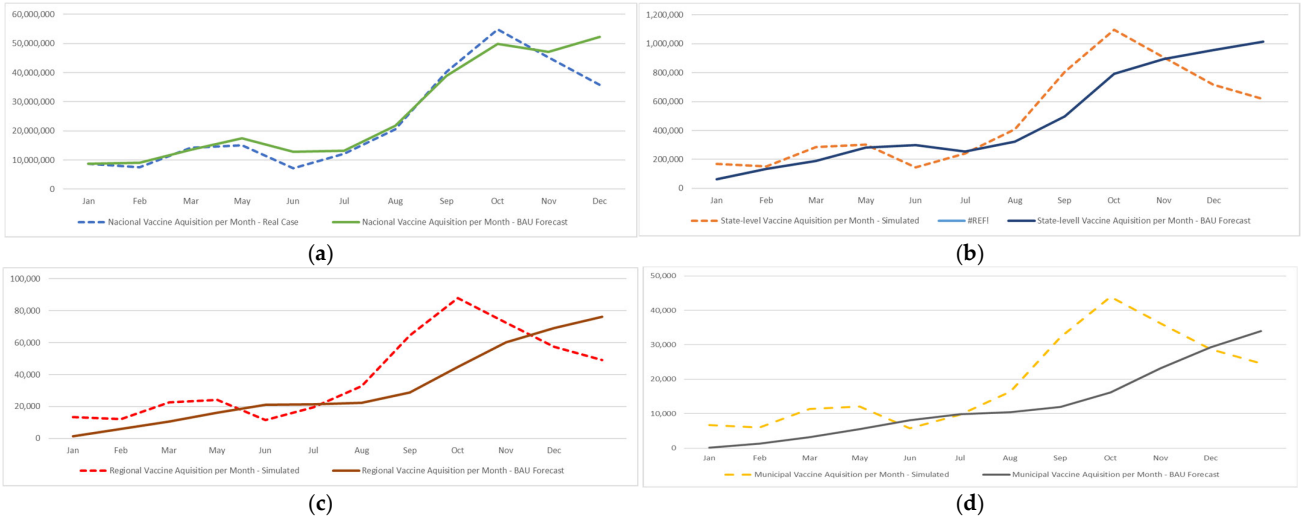


Figure 7. BAU and forecast-informed BAU scenarios for vaccine receipt at the national (**a**), state (**b**), regional (**c**), and municipal (**d**) levels.

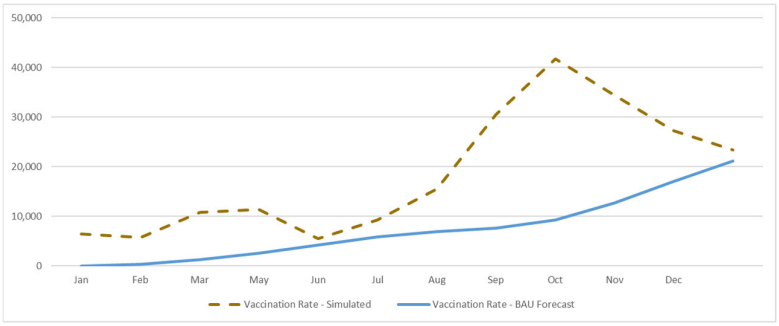


Figure 8. Monthly vaccination rates.

While the BAU Forecast configuration produces smoother vaccine inflows across levels, it does not translate into improved cumulative vaccination outcomes when downstream allocation proportions and distribution rules remain unchanged. In the BAU configuration, the monthly vaccination rate presents sharper peaks, especially in the second half of the year, whereas the BAU Forecast yields a more stable temporal profile. This contrast indicates that upstream predictability contributes to operational stability, but structural allocation constraints continue to dominate local performance.

Table 5 reports cumulative vaccinated individuals over 12 months for the real case, BAU, and BAU Forecast. Under the BAU Forecast, national procurement follows forecasted deliveries while preserving the same national-to-state, state-to-regional, and regional-to-municipal allocation ratios. Although this configuration smooths inflows, cumulative

vaccination remains close to the real observed outcome and substantially below BAU, reinforcing that improved receipt regularity alone is insufficient to increase cumulative performance under an unchanged distribution structure.

Table 5. Cumulative vaccination outcomes.

	Vaccination Rate—Real Case	Vaccination Rate—Simulated	Vaccination Rate—BAU Forecast
Total (12 months)	84,374	221,983	88,815
Variation	100%	+163%	+5%

Table 6 defines the simulated scenarios in terms of procurement logic, transport capacity parameters, and municipal vaccination capacity. BAU reproduces the observed procurement dynamics through the intermunicipal consortium, whereas BAU Forecast replaces procurement quantities with forecasted values while maintaining downstream allocation proportions. This distinction confirms that differences between these scenarios lie primarily in the receipt logic rather than in allocation rules, which is essential for interpreting the cumulative outcomes reported in Table 5.

Table 6. Scenario parameterization.

Scenarios	Procurement	National Transportation	State-Level Transportation	Regional Transportation	Municipal Vaccination Capacity
Base scenario	Real	2.00%	8.00%	50%	100%
Forecast scenario	Forecasted	2.00%	8.00%	50%	100%
A—Transport capacity 1	Real	6.00%	8.00%	50%	100%
B—Transport capacity 2	Real	2.00%	7.50%	50%	100%
C—Movement capacity	Real	2.00%	8.00%	52%	100%
D—Vaccination capacity	Real	2.00%	8.00%	50%	50%
E—Ideal scenario	Real	6.00%	7.50%	52%	100%
E—forecast	Real	6.00%	7.50%	52%	100%

4.2. Comparative Analysis of Scenarios

The simulation results for the alternative scenarios are presented in Figures 9–15, which illustrate the cumulative number of vaccinated individuals (beneficiaries) compared with the BAU scenario. Overall, the figures show that modifying distribution parameters at different logistical levels affects both the timing and the magnitude of vaccination outcomes throughout 2021, with stronger effects when changes occur upstream or when downstream operational capacity is constrained.

Scenario A produces higher vaccination trajectories throughout the year, with a pronounced divergence from BAU starting in mid-2021. This outcome reflects the adjustment of the national-to-state allocation, whereby Paraná receives a population-proportional share of vaccines.

By the end of the year, Scenario A yields 665,949 vaccinated individuals, exceeding the municipality's eligible population. As the model does not impose an explicit population constraint or demand saturation mechanism, this result should not be interpreted as a realistic projection, but rather as an expression of the system's potential logistical capacity

under ideal upstream coordination. In this sense, the obtained value represents a theoretical upper bound prior to saturation, indicating that correcting upstream allocation is sufficient to remove supply constraints at the municipal level within the model's structure. The magnitude also suggests that, when upstream allocation is corrected while downstream parameters remain unchanged, the simulated flow may accumulate excessively at the municipal level, evidencing excess logistical capacity unless an explicit population constraint is imposed.

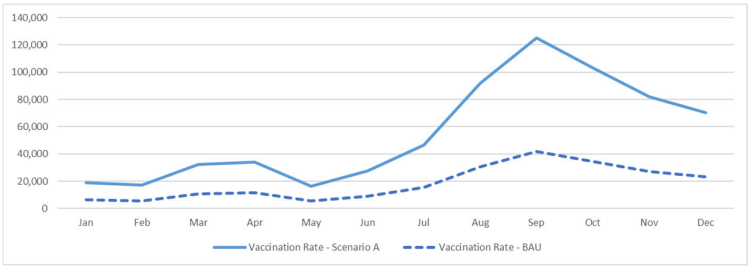


Figure 9. Scenario A x BAU.

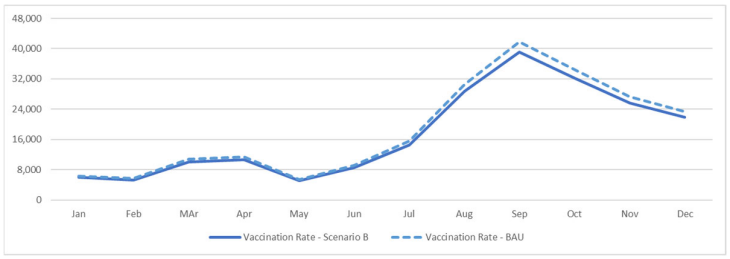


Figure 10. Scenario B x BAU.

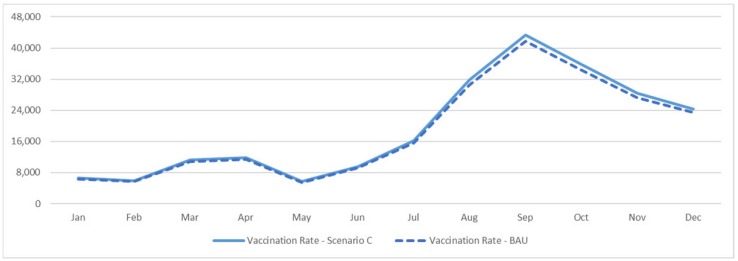


Figure 11. Scenario C x BAU.

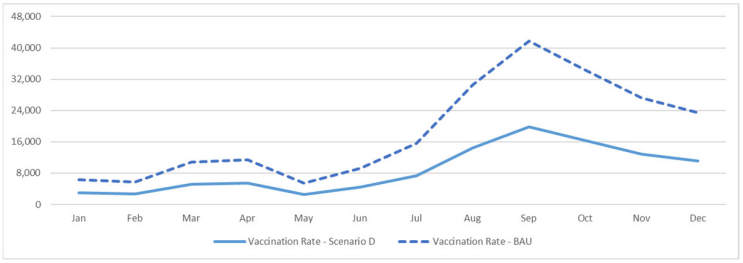


Figure 12. Scenario D x BAU.

Scenario B modifies only the distribution capacity from the state of Paraná to the 15th Health Region, while all other parameters remain unchanged. Consequently, monthly vaccination curves remain close to the BAU trajectory, with only minor deviations emerging in the second half of 2021.

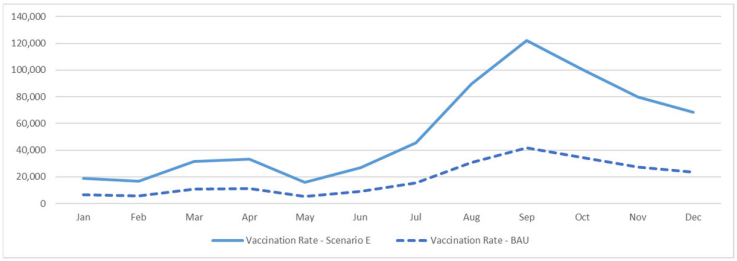


Figure 13. Scenario E x BAU.

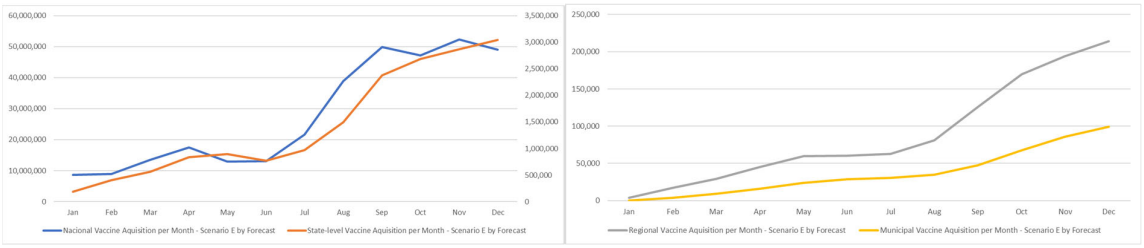


Figure 14. Vaccine inflows under Scenario E with forecast-informed procurement.

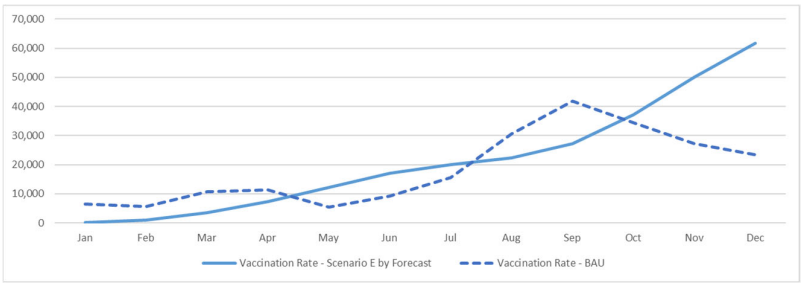


Figure 15. Monthly vaccination rates under the BAU and Scenario E with forecast-based procurement.

In cumulative terms, Scenario B vaccinates 208,109 individuals, compared to 221,983 in BAU. This reduction reflects the decrease in the state-to-regional capacity, which becomes more proportional to population but operates under an already constrained upstream allocation. The result indicates that isolated mid-chain adjustments have limited ability to improve outcomes when national-to-state allocation remains restrictive.

Scenario C introduces a marginal adjustment in the regional-to-municipal distribution by increasing the municipality's share from 50% to 52% of the doses allocated to the 15th Health Region, while all other parameters remain unchanged.

The monthly vaccination profile remains close to BAU, with slightly higher values from mid-2021 onward. In cumulative terms, vaccinated individuals increase from 221,983 in BAU to 230,862 in Scenario C. This modest gain indicates that local corrections at the regional-to-municipal interface can improve outcomes, but their overall effect remains limited when upstream allocation constraints persist.

Scenario D reduces municipal vaccination capacity to 50%, representing constraints in inputs such as syringes, workforce, or operational readiness, while keeping procurement and upstream distribution parameters unchanged.

Monthly vaccination remains consistently below BAU throughout the year, with the gap widening during periods of higher vaccine availability. In cumulative terms, Scenario D vaccinates 105,150 individuals, substantially below BAU (221,983). Missed doses increase markedly, from 11,683 under BAU to 128,517 under Scenario D, showing that downstream operational capacity can become the dominant driver of performance and can outweigh improvements in vaccine availability and distribution.

Scenario E represents an idealized upper-bound structural configuration of the vaccination supply chain, in which transport and vaccination capacities across governance levels are proportionally aligned with population shares, eliminating the structural underallocation observed in BAU. Under Scenario E with real procurement, vaccination rates increase sharply from mid-2021 onward and remain above BAU. From an efficiency perspective, this configuration enables a faster conversion of available doses into vaccinations, indicating that supply would not be a binding constraint under a fully coordinated distribution system. In cumulative terms, the model indicates that the eligible population in the municipality (338,012 individuals aged over 18 years) would have been fully vaccinated within the year, as shown in Table 7, implying that the aggregate volumes delivered by the consortium would have been sufficient if internal distribution and allocation mechanisms were adequately organized.

Table 7. Cumulative vaccinated individuals in the municipality.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Beneficiaries (accumulated)—CEN Eaq	18,700	35,368	66,955	100,401	116,414	143,348	188,849	278,408	400,468	501,105	580,861

Vaccination increases rapidly over time, surpassing 188,000 individuals by July and exceeding the eligible population between August and September. In terms of equity, the proportional allocation across all levels ensures alignment between vaccine flows and population shares, reducing the mismatches observed in BAU. With respect to the vaccination timeline, this result reinforces that, under an ideal internal distribution structure, the limiting factor would shift from vaccine availability to downstream organization and execution.

Figures 14 and 15 present Scenario E under forecast-based procurement, in which vaccine inflows follow the quantities estimated as necessary each month. Compared to BAU, receipts at the regional and municipal levels exhibit smoother trajectories and reduced month-to-month volatility. From an efficiency standpoint, this results in a more consistent use of capacity over time. Monthly vaccination rates also evolve more evenly, avoiding the sharp peaks observed under BAU and indicating a more stable operational environment for local health services. In terms of equity, the proportional allocation structure is preserved, maintaining alignment between supply and population needs across all levels.

In cumulative terms, Scenario E with forecast-based procurement results in 259,784 vaccinated individuals by the end of 2021, compared to 221,983 under BAU. Although this outcome remains below the upper-bound result associated with Scenario E under real procurement, it highlights a trade-off between temporal stability and rollout speed: aligning deliveries with forecasted needs improves the regularity of vaccination dynamics while still increasing cumulative outcomes under the Scenario E structural configuration.

Table 8 summarizes vaccine receipts at each level and the corresponding number of vaccinated individuals across scenarios. The comparison indicates that distortions originate primarily at the national-to-state allocation level, where systematic underallocation to Paraná constrained downstream availability. Even when proportional corrections were introduced at regional or municipal interfaces, their effects remained limited when upstream allocation continued to diverge from population-based benchmarks. Consequently, upstream distortions propagated along the chain and became increasingly visible at the municipal level, where vaccination outcomes ultimately materialized.

Table 8. Vaccine receipt and vaccination outcomes across scenarios.

Scenario	National Receipt	State Receipt	Regional Receipt	Municipal Receipt	Vaccinated Individuals
Real case	302,120,233	5,828,751	442,494	233,187	221,528
BAU	292,373,217	5,841,663	467,333	233,667	221,983
BAU Forecast	292,373,217	5,841,663	467,333	233,667	88,815
Scenario A	292,373,217	17,524,988	1,401,999	700,999	665,950
Scenario B	292,373,217	5,841,663	438,125	219,062	208,109
Scenario C	292,373,217	5,841,663	467,333	243,013	230,862
Scenario D	292,373,217	5,841,663	467,333	233,666	105,150
Scenario E (real procurement)	292,373,217	17,524,988	1,314,374	683,474	649,301
Scenario E (forecast-based)	333,892,294	17,109,388	1,063,582	447,867	259,784

One limitation of the model is the use of average transport capacity parameters over the simulation horizon. In practice, allocation percentages varied substantially from month to month. For example, national-to-state transfers to Paraná ranged from approximately 4% in July to 0.6% in October, never reaching the population-proportional benchmark of 6%. These temporal fluctuations were not explicitly modeled and may reflect bullwhip-type effects driven by volatility in national deliveries. Under forecast-based procurement, smoother upstream inflows dampen this variability, reinforcing the systemic role of upstream uncertainty.

5. Discussion

The results reveal a persistent misalignment between forecasted vaccine demand and actual procurement during the municipality's COVID-19 vaccination campaign. Approximately 86% of the projected doses were effectively delivered, indicating a structural gap between planning assumptions and realized supply. Rather than reflecting short-term operational failures, this discrepancy points to weaknesses in the preparation phase, where procurement decisions were insufficiently aligned with population-based demand and local operational capacity. Similar shortcomings have been identified in evaluations of Brazil's National Vaccination Plan, which reported spatial and infrastructural mismatches that constrained equitable access to immunization services, particularly among vulnerable populations [8]. The case analyzed illustrates how upstream planning deficiencies propagate downstream and materialize as localized performance constraints within a decentralized system.

From a humanitarian logistics perspective, these findings empirically reinforce the principle that preparedness precedes response. However, the results also indicate that the relationship between these phases is not strictly sequential. In the analyzed case, key preparation activities—such as procurement adjustments, allocation decisions, and operational structuring—continued to evolve during the response phase. This overlap introduced coordination challenges, as upstream decisions were frequently revised under ongoing operational pressure, generating inconsistencies in supply flows and misalignment with local capacity. This insight aligns with foundational and contemporary contributions in humanitarian logistics, which emphasize preparedness as a determinant of effective emergency response [7,10]. When preparation is fragmented, response efforts rely on reactive adjustments, leading to inventory imbalances and inefficient resource use. Similar

dynamics were observed in other decentralized COVID-19 responses, where coordination gaps amplified territorial inequalities.

The comparative analysis across Scenarios A, B, and C highlights the limited effectiveness of isolated interventions within multi-level distribution systems. Adjustments at intermediate interfaces produced marginal gains when upstream allocation remained misaligned. Conversely, correcting national-to-state allocation in isolation generated accumulation effects, revealing the systemic interdependence of allocation rules. These results suggest that distribution efficiency depends less on single-parameter corrections and more on coherence across governance levels. In federative systems characterized by autonomy and shared responsibilities, coordination mechanisms become structural determinants of equity and performance [3].

Operational capacity at the point of service emerged as another decisive determinant of vaccination performance. Scenario D demonstrates that reductions in municipal vaccination capacity substantially decrease coverage and increase missed doses, even when supply is maintained. Vaccine availability alone does not guarantee immunization outcomes. Complementary inputs, workforce readiness, and infrastructure are integral components of preparedness. This finding aligns with studies showing that cold chain integrity and operational coordination are as critical as procurement volumes [26].

The comparison between BAU and BAU Forecast clarifies that supply predictability is not equivalent to preparedness. Forecast-aligned procurement smooths inflows but does not improve cumulative outcomes under misaligned allocation rules. Preparedness requires alignment between forecast, procurement, and proportional allocation mechanisms. Equity in distribution is therefore not solely a normative objective but a performance condition [27,28].

The idealized scenario provides an analytical upper bound, demonstrating that, under proportional allocation and adequate capacity, delivered volumes would have been sufficient to achieve full coverage within a shorter period. This indicates that the structural design of allocation rules played a more decisive role than aggregate supply volumes. The current SUS distribution model, which combines centralized procurement with decentralized execution, ensures capillarity and territorial reach. Still, the simulations suggest that allocation distortions at upper levels may compromise equity at the local level. A more equitable configuration would require transparent population-based allocation criteria, dynamic redistribution mechanisms responsive to real-time uptake, and strategic safety stocks at state and regional levels to buffer procurement volatility.

While these scenarios provide useful analytical insights, their implementation in real emergency contexts may face practical constraints. Allocation decisions during the COVID-19 vaccination campaign were influenced not only by technical criteria but also by coordination challenges across governance levels, time pressure, and operational limitations. In decentralized systems, factors such as data availability, infrastructure differences, and institutional dynamics can affect the feasibility of strictly proportional distribution rules. Therefore, the scenarios should be interpreted as analytical references to explore system behavior and identify inefficiencies, rather than as directly implementable solutions.

Although the findings reinforce well-established principles in humanitarian logistics, such as the importance of preparedness and coordinated allocation, the results also provide additional insights. In particular, the analysis shows that supply predictability alone does not necessarily translate into improved vaccination outcomes when allocation mechanisms remain misaligned across governance levels. Furthermore, the study demonstrates how distortions in upstream allocation propagate through decentralized systems and constrain downstream performance, while isolated adjustments at intermediate or local levels produce limited effects. These findings suggest that preparedness should be understood as a

systemic alignment between procurement, allocation, and operational capacity, rather than as a set of isolated planning activities.

Despite these contributions, limitations remain. The model uses average-capacity parameters and does not incorporate behavioral or stochastic dynamics, such as hesitancy or workforce variability. Future research could integrate hybrid modeling approaches to capture these dimensions.

Policy implications: The simulations suggest three practical recommendations for health managers. First, vaccine stock policies should incorporate strategic buffer inventories at state and regional levels to absorb procurement volatility without generating local shortages. Second, allocation mechanisms should be dynamically adjusted according to demographic structure and real-time coverage indicators, rather than relying solely on static proportional rules. Third, preparedness plans should formally integrate distribution and service capacity assessments to ensure that procurement decisions are synchronized with downstream operational readiness. Socially, the study highlights that allocation distortions in decentralized systems can translate into unequal access and delayed protection for medium-sized cities, reinforcing the need for transparent and coordinated intergovernmental planning to enhance equity and resilience in future public health emergencies.

6. Conclusions

This study analyzed the COVID-19 vaccination campaign conducted in the municipality of southern Brazil from a humanitarian logistics perspective, with an emphasis on the interaction between the preparedness and response phases. Using a case-study approach supported by scenario-based simulation, this research examined how constraints in vaccine procurement, allocation across governance levels, and municipal operational capacity shaped vaccination outcomes in 2021. Rather than seeking to optimize the campaign, the analysis assessed how different logistical configurations could have affected performance under emergency conditions.

The results demonstrate that vaccination outcomes were not determined solely by global vaccine availability, but primarily by how procurement and distribution decisions were structured across national, state, regional, and municipal levels. The BAU scenario, which reproduced the observed campaign dynamics, showed that the municipality vaccinated 221,983 individuals by the end of 2021, closely matching empirical data. Scenario comparisons revealed that adjustments limited to intermediate levels of the supply chain produced marginal effects, while upstream underallocation at the national–state interface consistently constrained downstream performance. Conversely, scenarios combining improved procurement alignment and adequate operational capacity indicated substantially higher vaccination potential, highlighting the magnitude of unrealized system capacity.

From a disaster risk management perspective, these findings reinforce the principle that preparedness must precede response. The observed gap between forecasted and realized vaccine supply, with only 86% of projected doses effectively delivered, reflects a structural limitation in the preparation phase. This shortfall forced the campaign to operate reactively, generating downstream inefficiencies such as inventory imbalances, missed doses, and underutilization of municipal capacity. The results indicate that supply predictability alone is insufficient to improve outcomes if allocation mechanisms and operational readiness are not simultaneously addressed.

Methodologically, the study illustrates how scenario-based simulation can be used as an analytical tool to explore the systemic consequences of alternative logistical arrangements in emergency vaccination campaigns. By representing the vaccination supply chain through aggregated stock-and-flow structures, the model enabled comparison of scenarios and identification of leverage points without relying on epidemiological forecasting or

behavioral assumptions. This approach contributes to humanitarian logistics research by empirically linking preparation-related decisions to observed operational outcomes in a decentralized public health system.

The analysis also offers practical insights for policymakers and public managers. The findings suggest that proportional allocation and coordinated planning across governance levels are not only normative goals but also determinants of logistical efficiency. Strengthening preparation mechanisms, securing more reliable procurement processes, and aligning distribution rules with demographic needs are critical to improving performance at the municipal level, where vaccination ultimately occurs. In addition, ensuring adequate local operational capacity in terms of workforce, inputs, and infrastructure is essential to translate vaccine availability into effective coverage.

Some limitations must be acknowledged. The analysis focused on a single municipality and on two vaccines, Coronavac and Pfizer, which limits generalization to other contexts and immunizers with different logistical requirements. The model also relied on average-capacity parameters and did not incorporate stochastic variability or behavioral dynamics, such as vaccine hesitancy or workforce fluctuations. Future research could address these limitations by extending the analysis to multiple municipalities or higher administrative levels, incorporating additional vaccines, and combining simulation with stochastic or agent-based approaches to better capture uncertainty and behavioral effects.

Overall, this study highlights that failures in preparedness and coordination can significantly undermine the effectiveness of emergency vaccination campaigns, even when vaccine supplies are available. By demonstrating how upstream decisions propagate through decentralized systems, the findings underscore the importance of integrated planning and logistical readiness for strengthening resilience in future public health emergencies.

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