A Goal Programming model to support decisions in the acquisition of vaccines against COVID-19 at the municipality level

Joaquim Lima das Neves Neto[1]; Leonardo Cardoso Galvão[1]; Pollyana de Nazare Cordeiro dos Reis[1]; Renata Melo e Silva de Oliveira[1] [0000-0002-1904-7533]

[1] Universidade do Estado do Pará, Pará, Brazil

renata.olveira@uepa.br

Abstract. The objective of this study is to present a goal programming formulation to support the emergency acquisition of vaccines**.** The model specified applies to the context of decision-making at the municipality level. The criteria selected include pandemic public management decision-making problems such as budget limitations, setting goals for the immunization of priority population groups, and recommendations of the World Health Organization (WHO). The guidelines of the Brazilian Unified Health System (UHS, in Portuguese, Sistema Único de Saúde - SUS) are also sought. The scenarios specified using the GP model are applicable to municipalities in need to acquire optimized supply amounts to execute the heterologous immunization program in the year 2022, given the budget limitations. An application of the methodology was conducted using data from the city of Belem, the capital of Para State. Managerial implications and foreseen research opportunities are discussed by the end of this paper**.**

Keywords: Goal Programming, Unified Health System, Immunization Plan, COVID-19.

1 Introduction

This study specifies a Linear Goal Programming Model to optimize the number of vaccines acquired by a Brazilian Capital city, taking into account the Unified Health System (UHS) criteria of reinforcement immunization against COVID-19 and the recommendations of the World Health Organization (WHO)[2]. This applied study was developed in the context of the second cycle of vaccination against SARS-CoV-2 executed in the first semester of 2022. At that time, the budget constraints for the acquisition of second and third doses in the public health system raised relevant issues regarding how to execute the vaccination plans at the municipality level.

The pandemic caused by SARS-CoV-2 raised exposed a range of gaps in the protocols of immunization for multiple-dose programs. In Brazil, this can be explained by the complex processes involving the acquisition, storage, and distribution of vaccines in a period of 3 months and reaching bold quantitative goals.

In Brazil, emergency vaccination plans and the acquisition of supplies are the responsibility of the municipalities but the budget allocation is defined at Federal Level. Thus, this is not uncommon that large and wealthy municipalities to benefit from bargaining power over struggling small towns and are pushed to the bottom of the line due to their reduced budget possibilities.

In this context, municipalities would benefit from a procedure based on quantitative criteria to make decisions of this sort (e.g., brand selection, budget allocation, territory configuration, and population peculiarities). Therefore, the optimization of the acquisition of doses for immunization against COVID-19 should be tailored according to both the recommendations of WHO and the goals set by the Brazilian Health Ministry for each municipality[1].

An application of this methodology is also presented. It involves the specification of decision scenarios is also discussed. The city studied is Belem, the capital of Para State. The city of Belem is considered the most populous municipality in the State of Para. It is also the second-largest city in the North region, with a population of 1 506 420 inhabitants[3].

This paper is organized as follows. Section 2 is the methodology section. It reports the optimization problem formulated for this study. Section 3 discussed the results obtained with an application using data from the city of Belem, in the Brazilian Amazonian region. Three decision scenarios are also explored. Section 4 finalizes this article by unveiling the main conclusions attained with the scenario analysis. The last section of this paper also contains prospects for future research in this field.

2 Methodology

2.1 The Goal Programming Model

Goal Programming (GP) is a technique based on linear programming (LP) used to approach multiple and conflicting objectives in the same problem. It can be considered a branch of the multi-objective optimization field in the subdomain of multi-criteria decision-making/analysis (MCDM/A). GP was introduced by Charnes et al., (1955) [4] and Charnes and Cooper (1961)[5]. Soon after, it gained notoriety in a range of applications that included mixed optimization methods [6]–[12].

A problem involving goal programming must take into consideration a set of target values to be achieved by each equation specified. Potential deviations from the target are highly likely to occur. Therefore, these undesirable deviations are the decision variable to be minimized in the objective function.

Another characteristic of GP models is that there are multiple objectives, which are prioritized according to their relative importance to the decision-maker. The constraints represent the goals to be performed involve hard constraints and soft constraints. Hard constraints are inequalities representing conditions that need to be satisfied before goal constraints. Flexible constraints are equations that represent organizational objectives and goals to be achieved.

To quantify the prioritization of objectives, flexible constraint equations accommodate deviation variables, which can be positive or negative. Positive deviation variables greater than zero indicate that a certain target was exceeded. Negative variables represent results below your target.

Model (1) reports the GP linear problem specified for this study.

$$
\begin{aligned}
&Min\ Z: \sum_{i=1}^{r} p_i\ (d_{ij}^{+} + d_{ij}^{-}) \\
&s.t. f_{ij}(X) - d_{ij}^{+} + d_{ij}^{-} = g_{ij} \qquad i = 1,\ \dots,\ r \quad j = 1 \dots, s \\
&\qquad a_i x_{ij} \le b_{ij} \\
&\qquad d_{ij}^{+},\ d_{ij}^{-} \ge 0, \qquad\qquad \forall i\ \forall j
\end{aligned}
\tag{1}
$$

In model (1), i $(i = 1,\ \dots,\ r)$ is the set of vaccine brands and j $(j = 1 \dots, s)$ is the set of municipalities considered in the problem. The objective function Z seeks to minimize the sum of all positive (d_{ij}^{+}) and negative (d_{ij}^{-}) deviations from the target values of the goals (g_{ij}). p_i are strictly positive values assigned for each deviation by the decision-maker. X is a matrix representing the number of doses to be acquired of each brand of vaccine for the second and third rounds of immunization according to the target values set by g_i. Therefore, $f_i(X)$ is equality that represents all flexible constraints associated with the goals. In the third line of (1), the set of rigid constraints can be interpreted identically to the constraints of a classical LP problem.

3 Application

3.1 Criteria Framework and data collection

The criteria selected for the combination of brands for heterologous immunization followed the recommendations of the Brazilian Health Minister [1] and the World Health Organization[2]. The recommendations are the following UHS estimated demand for additional vaccination for the adult populations; the annual budget for COVID-19 vaccines; the mandatory compatibility between manufacturers of doses 1 and 2 with those of dose 3. Vaccines produced by six laboratories were taken into account. This information was used to define targets associated with vaccine brands such as AstraZeneca, Pfizer, and CoronaVac [13].

Data were collected from three official Brazilian Federal Government open databases to reflect framework criteria for decision-making. The data sources adopted in this research are described in the next paragraphs.

The OpenDATASUS [14] provided information to analyze the population's health situation. It systematizes, evidence-based decision-making and the development of health action programs.

The purpose of the Brazilian National Immunization Program Information System (SI-PNI)[15] is to enable managers involved in the program to perform a dynamic risk assessment regarding the occurrence of outbreaks or epidemics, based on the registration of the vaccinated population.

The Institute of Studies for Health Policies (IEPS)[16] is a non-profit organization that works mainly in the production of scientific research, and proposition of public policies. IEPS made available data on scheduling acquisition and distribution of vaccines against COVID-19. Table 1 reports the unitary cost of the three vaccine brands acquired by the municipality of Belem (Pa) by December of 2022. This table also reports the official number of adults from 18 to 80+ vaccinated by March 2022.

Table 1 Population Vaccinated by March 2022

Vaccine Brand	Unitary cost (BRL)	Population vaccinated		
		1st dose	2nd dose	3rd dose
AstraZeneca	15.85	243,545	222,752	1,644
Pfizer	60.20	638,128	579,998	162,578
Coronavac	58.20	261,850	240,997	4,703
Total		**1,143,524**	**1,043,747**	**168,925**

Table 2 reports the municipal goal for adults to be vaccinated with the third dose in 2022. It also reports the number of citizens to receive a late second dose of the vaccination. These target values are based on the guidelines established by Technical Note 43/2021-GAB/SECOVID/MS[13] and the normative entitled "Operationalization of vaccination against COVID-19/2022" [1].

Table 2 – Demand of Population to vaccinate after March of 2022

Vaccine Brand	Population to vaccinate	
	2nd dose	3rd dose
AstraZeneca	20 793	241 901
Pfizer	58 130	475 550
Coronavac	20 853	257 147

The amount of BRL 3.9 billion was adopted as the budget hard constraint foreseen by the Brazilian Federal Government Annual Budget Law 14303 [17], [18].

3.2 Specification of parameters

The parameters specified took into account the criteria presented in subsection 3.1. The optimization of the acquisition plan of vaccination in Belem used the following information.

- Amount of vaccine brands to be acquired as **second** doses
  x_1: AstraZeneca
  x_2: Pfizer
  x_3: Coronavac
- Amount of vaccine brands to be acquired as **third** doses
  x_4: AstraZeneca
  x_3: Pfizer

The soft constraints $f_i(X)$ were specified as follows.

- $f_1(x)$: number of **AstraZeneca** vaccines to be acquired as a second dose for citizens that received the same brand in the first dose.

- $f_2(x)$: number of **Pfizer** vaccines to be acquired as a second dose for citizens that received the same brand in the first dose.
- $f_3(x)$: number of **Coronavac** vaccines to be acquired as a second dose for citizens that received the same brand in the first dose.
- $f_4(x)$: number of **Pfizer** vaccines to be acquired as the third dose for citizens that received **Astrazeneca** as the first dose.
- $f_5(x)$: number of **Astrazeneca** vaccines to be acquired as the third dose for citizens that received **Pfizer** or **Coronavac** as the first dose.

The goals g_i were formulated as follows:

- g_1: 20 793
- g_2: 58 130
- g_3: 20 853
- g_4: 241 901
- g_5:475 550 + 257 174 = 732 697

Note that for each parameter listed, a par of deviational decision variables $(-d_i^+,\ d_i^-)$ was introduced in (1).

Finally, the decision-making scenarios were formulated according to the recommendations of an expert opinion in the field of decision-making processes of this sort. The scenarios are listed in the next paragraphs.

- **Scenario A:** No priorities and no penalization for positive deviations. Thus,
  - $p_1 = p_2 = p_3 = p_4 = p_5$ (priority ≈ 20%).

Scenario A can be considered a naive scenario because it implies the reinforcement of third doses is as much priority as completing the immunization of the adult population with the second dose. This scenario penalizes equal deviations of the goals set for all brands to be acquired as doses 2 and 3.

- **Scenario B:** No penalization for positive deviations. Completing vaccination coverage of the 2nd dose is five- times more important than initiating 3rd doses vaccinations. Thus,
  - $p_1 = p_2 = p_3 = 1$ (priority ≈ 29.41%)
  - $p_4 = p_5 = 0.2$ (priority ≈ 5.88%)

Scenario B prioritizes the fulfillment of the immunization of the adult population according to WHO. It implies that the optimization model penalizes more severe outcomes with deviations from the goal set for g_1 to g_3 (doses number 2). This scenario also assumes that Buys Pfizer and AstraZeneca as third doses are equally important. This assumption follows the strategy that the unitary cost of the brands is indifferent to the costs of acquisition.

- **Scenario C:** No penalization for positive deviations. Prioritizing acquisitions according to the following levels of preferences. The 2nd doses of

Astrazeneca, Coronavac, and Pfizer brands are five times more important than the 3rd doses of Astrazeneca brands. The 3rd dose of Pfizer is three-time more important than the 3rd dose of AstraZeneca. Thus,

- $p_1 = p_2 = p_3 = 5$ (≈ 26.3% priority)
- $p_4 = 3$ (≈16% priority)
- $p_5 = 1$ (≈ 5.2% priority)

Scenario C also takes into account the WHO and UHS guidelines. The difference from scenario B is that the strategy of cos-efficiency maximizes the use of the budget to buy the highest number of doses possible. Therefore, there is a hierarchical rationale for prioritizing the completion of the second dose to be acquired. Regarding doses 3, the acquisition of AstraZeneca as dose 3 is prioritized. The lowest priority of acquiring Pfizer is dose 3, which is the brand with the highest unitary cost of acquisition.

3.3 Results

Tables 3 and 4 report the results obtained with the optimization formulation (1). Scenario A ensures partial coverage of the municipality vaccination plan for the acquisition of both doses 1 and 2. If a decision-maker chooses scenario A, $f_1(x)$ would reach 82.29% of the target value (g_1) defined. On the other hand target values from g_2 to g_5 would be fully achieved. This means that 3 683 people in need of Astrazeneca doses would not be immunized in Belem in 2022, given the budget allocated to this municipality. The population in need of Pfizer vaccines as a 2nd dose and AstraZeneca as the 3rd dose would be fully covered though.

Table 3 – Three decision scenarios for acquisition planning of vaccines

Vaccines to acquire	Scenarios		
	A	B	C
AstraZeneca (x_1)	17 110	20 793	20 793
Pfizer (x_2)	0	58 130	0
Coronavac (x_3)	0	20 853	0
AstraZeneca (x_4)	0	0	0
Pfizer (x_5)	73 5967	464 976	729 014
$\sum_i x_i$	753 077	564 752	749 807

Scenario B ensures that the federal program is fulfilled in terms of acquisition of doses number 2 for both AstraZeneca, Pfizer, and CoronaVac. However, third doses would be in shortage by 60%. However, the target values of $f_4(x)$ would be overlooked and that $f_5(x)$ would meet approximately 63% of its target value (g_5) in this scenario. This means that the immunization of the adult population would be completed and approximately 40% of the necessary doses for reinforcement vaccination using Astrazeneca as the third dose would be feasible.

Table 4 –Potential unmet demand per scenario

Unmet demand	Scenarios		
	A	B	C
d_1^+	-		
d_1^-	3 683	0	0
d_2^+	-	-	-
d_2^-	58 130	0	58 130
d_3^+	-	-	-
d_3^-	20 853		20 583
d_4^+	-	-	-
d_4^-	241 901	241 901	241 901
d_5^+	-	-	-
d_5^-	0	267 721	36 83
z	324 567	509 622	324 567

Scenario C can be considered Cost-Efficient. In this scenario, the values of $f_1(x)$ and $f_5(x)$ would ensure that AstraZeneca is the predominant brand applied to the population. Note that in terms of cost-efficiency, this brand offered the most competitive set in the brand. Despite the deviations observed in the variables ranging from d_2^- to d_5^-. However, all the other goals would be at least 60% below the targets stipulated in the national vaccination plan for the municipality to execute.

Considering the three scenarios analyzed, scenario B can be considered the most feasible. This can be explained since the budget limit defined by law for the municipality of Belem cannot be exceeded. Furthermore, scenario B allows for maximizing the basic vaccination coverage of the 2nd dose of vaccine. In addition to allowing the partial execution of the action plan for the 3rd dose of immunizations for the population.

4 Conclusions

This paper reported the use of the goal programming approach to address the challenging task of emergency vaccine acquisition. GP is considered a well-known approach to addressing decision problems involving multi-criteria conflicting objectives.

The model specified can support decision-makers in the selection of the optimized amount of doses according to criteria such as the population needs, the brands available in the market, and recommendations of WHO toward heterologous immunization requirements. The budget constraint was also sought.

One of the main features worth noting in formulation (1) is the possibility of combining this technique with the analytical hierarchy process analysis of goals. The estimation of weights assigned to the decision variables (d_{ij}^+ and d_{ij}^-) can reflect managerial preferences as much as the relative importance of the priorities set for population groups to be immunized.

In the case of the application reported here, we resorted to an expert's opinion to st the weights in scenarios A, B, and C. Therefore, the data feeding model (1) can support decisions on purchasing vaccines against COVID-19 by the Brazilian Municipality Belem. Therefore, this paper discussed the most suitable scenario for meeting the needs of the city studied to use public resources for maximizing population coverage of second doses and simultaneously start the complementary heterologous immunization by March of 2022.

As research opportunities, it is highly recommendable to refine the choice methods of weights (p) by exploring the impacts associated with the results. Statistical robustness in the weighting method should be sought as well.

References

1. *MINISTÉRIO DA SAÚDE, OPERACIONALIZAÇÃO DA VACINAÇÃO CONTRA A COVID-19. Brasi, 2021, p. 136.*
2. World Health Organization., "Interim recommendations for heterologous COVID-19 vaccine schedules Interim guidance," no. December. World Health Organization, Geneva, pp. 1–18, 2021.
3. *IBGE, "IBGE Cidades," Belem, 2022. Online. Available: https://cidades.ibge.gov.br/brasil/pa/belem/panorama. last accessed: 08-Apr-2022.*
4. A. Charnes, W. Cooper, and R. Ferguson, "Optimal estimation of executive compensation by linear programming," Manage. Sci., vol. 1, pp. 138–1 5, 1955.
5. A. Charnes and W. W. Cooper, Management Models and the Industrial Applications of Linear Programming. New York: John Wiley & Sons, 1961.
6. M. J. McGregor and J. B. Dent, "An application of lexicographic goal programming to resolve the allocation of water from the Rakaia River (New Zealand)," Agric. Syst., vol. 41, no. 3, pp. 349–367, 1993.
7. C. Romero, Handbook of Critical Issues in Goal Programming, 1st ed. Cordoba: Pergamon Press, 1991.
8. J. Johnes and G. Johnes, "Research funding and performance in U.K. University Departments of Economics: A frontier analysis," Econ. Educ. Rev., vol. 14, no. 3, pp. 301–314, Sep. 1995.
9. R. Oliveira, A. Zanella, and A. S. Camanho, "The assessment of corporate social responsibility: The construction of an industry ranking and identification of potential for improvement," Eur. J. Oper. Res., vol. 278, no. 2, pp. 498–513, Oct. 2019.
10. P. Morais and A. S. Camanho, "Evaluation of the performance of European cities with the aim to promote quality of life improvements," Omega, vol. 39, no. 4, pp. 398–409, 2011.
11. S. M. S. M. Lee, Goal Programming for Decision Analysis. Philadelphia: Auerbach pbblishers, 1972.
12. J. P. Ignizio, Goal programming and extensions. Lexington: Lexington Books, 1976.
13. S. Extraordin, D. Adicional, C. Nacional, and P. Nacional, *NOTA TÉCNICA Nº 43 / 2021-SECOVID / GAB / SECOVID / MS*. Brasília, 2021, pp. 1–8.
14. *SUS, "OpenDATASUS," About OpenDATASUS, 2022. Online. Available: https://opendatasus.saude.gov.br. last accessed: 08-Apr-2022.*
15. *SUS, "the Brazilian National Immunization Program Information System," PNI, 2022. Online. Available: http://pni.datasus.gov.br/. last accessed: 08-Apr-2022.*
16. *IEPS, "Institute of Studies for Health Policies," about us, 2022. Online. Available: https://ieps.org.br/institucional/quem-somos/.*

17. BRAZIL, “Law No. 14303 of January 21, 2022,” vol. 00. BRAZIL SENATE, Brasília, pp. 1–11, 2022.
18. BRASIL, “Anex I of the Law No. 14303 of January 21st, 2022,” vol. 63. BRAZIL, Brasilia, p. 2, 2017.