Mathematical optimization models for mass vaccination against COVID-19 in low and middle-income countries: Colombian case study

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Research practice II
Research proposal
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1 Statement of the problem

The COVID-19 pandemic, a product of the SARS-CoV-2 virus, has become a worldwide problem that continues to claim thousands of lives daily. This disease has not only challenged the health sector in each country, but has also weakened their economies, where the most affected, as reported by Yoshida *et al.* (2020), have been low and middle income countries. Particularly, Colombia is a middle-income country which has not been the exception in relation to the problems that this virus causes in its economy and its population (Sarmiento, 2019). This country has more than two million infected people and is among the twenty countries with more deaths due to this disease (Orús, 2021). Additionally, its health systems have been collapsed throughout the pandemic, where departments such as Norte de Santander have a current occupation of Intensive Care Units (ICU) above 80% (Minsalud, 2021a), and its economy has been greatly affected as evidenced by the increase in informal employment rates to 47.7% (DANE, 2020).

Due to the different advances in the production of vaccines and the contracts that Colombia has made with multiple producing organizations, the country is preparing to initiate a massive vaccination stage, which is crucial in mitigating the impact of the virus in the territory. As explained by Minsalud (2021d), the vaccination plan defined by the government expects to vaccinate 70% of the population, divided into five phases with respect to the risks of morbidity and exposure to the virus, in order to achieve herd immunity which will allow the population to overcome the devastating pandemic (Minsalud, 2021c). More than 34 million vaccines will arrive to the country, distributed in different periods, from the companies like Pfizer, AstraZeneca, Janssen, Moderna and Sinovac, which present notable differences in terms of storage temperature conditions, number of required doses per patient, effectiveness and shelf life (Colprensa, 2021). These vaccines will be distributed in all the territory of the country according to the prioritization defined by the government (Minsalud, 2020c), and where those with special temperature conditions will be allocated only to seven departments with adequate equipment for their containment (Minsalud, 2020b). This entire vaccination plan will be supported by 2900 vaccination points, with 7920 vaccinators and a nationwide vaccination capacity of 177,200 people per day.

Given the great affectation that COVID-19 has caused in Colombia at an economic and social level, the number of lives it has taken, and the recent millionaire investments to carry out the mass vaccination process, the country cannot afford to fail in the mitigation of the virus. This raises the question of how to optimally manage the vaccination process, taking into account economic, political, demographic and health factors, and integrating mathematical models of multi-objective optimization of allocation, distribution and transport, which represents an effective control of the spread and deaths by COVID-19 in Colombia. The results of this work seek to serve as a reference in the process of vaccine delivery to each territory, as well as in the vaccination process carried out by each vaccination center. The proposed models will take into account transport costs, population coverage, fair distribution and available resources.

2 Objectives

2.1 General objective

Propose mathematical optimization models to enhance the efficiency and logistics management of mass vaccination plans for COVID-19 virus mitigation in Colombia.

2.2 Specific objectives

- Review scientific literature about mass vaccination and related works.
- Identify factors and features of interest that influence the mass vaccination process in the local context.
- Formulate a vaccine allocation model for different time periods and regions of the country, considering factors such as equity in distribution, transportation costs and demographic characteristics of influence.
- Develop an optimization model focused on mass vaccination processes in vaccine centers, taking into account the requirements of personnel and equipment necessary to attend the different population groups established.
- Identify existing relationships between operations research techniques reported in the literature like simulation and optimization to consider integrated models.

3 Justification

The developments resulting from this research at the theoretical level represent a special interest, given that it is working on the basis of multi-objective models and evaluating different allocation and distribution processes. With this in mind, previous developments found in the literature will be considered and possible new models that may be useful for researchers in different areas will be proposed.

In a practical approach, as can be seen in Shen (2020), developments in applied mathematics, including optimization, have been of great use in the treatment of the pandemic. It is therefore important to continue investing in research with a social focus, especially in low and middle-income areas, as is the case in Colombia, where the COVID-19 disease has taken the lives of more than 50 thousand people and the number of confirmed cases exceeds two million (Minsalud, 2020a).

In addition to the current situation, some of the vaccines that are close to arrive in the country like Pfizer and Moderna, have such a requiriments as very low storage temperatures, where they could only last a maximum of 5 and 30 days in common freezers, respectively (Colprensa, 2021). This situation is worrying since, without the correct measures for distribution, personnel allocation and population coverage, doses of great utility for the susceptible population could be lost.

Situations of wastage of doses due to poor logistical planning have already been recorded. For instance, in Spain, due to the lack of adequate resources for mass vaccination campaigns, the syringes used in the vaccination process have caused the loss of approximately 34 855 vaccines (Jiménez, 2021). On the other hand, According to BBC News Mundo (2021), Israel had been vaccinated almost 19% of its population by february 2021. That's why, Avoiding the logistic inconvenience, and motivated by the positive advances of some countries, this project will focus on proposing mathematical optimization models that represent a great contribution in management, distribution and control of the mass vaccination process in the Colombian context.

4 Scope

This project will be focused on the analysis of vaccination processes in low and middle income countries, taking Colombia as a case study, where time and access to information limitations are the most influential. For this reason, the product of this research refers to mathematical optimization models that can support the evaluation of the action plans implemented in the massive vaccination process that will be carried out in the country until 2022. Since this development is based on a process for which there are no results, the models to be proposed will be generic, where the data to be used will be added as the vaccination in each territory progresses. In turn, the results obtained over a period of four months will be based on algorithms that use simulated data to evaluate different strategy scenarios, such as: prioritization of vaccines, influence of serological testing, drive-through vaccination, among others. These results will provide different alternatives for the distribution, allocation and transportation of personnel, vaccine doses and other resources for the optimal development of the mass vaccination process in Colombia.

The tools and resources to be used are divided into three parts: the first of these refers to the literature review and data collection, for which different bibliographic databases are used, such as ScienceDirect, with access through a license from Universidad EAFIT, and the governmental pages on COVID-19 in the country. In the second part we have the modeling and implementation, this will be performed by developing the models and algorithms to be implemented in the Python programming language, using the Gurobi extension for solving optimization problems. Finally, the last part refers to communication, which will be carried out by means of periodic meetings through the Microsoft Teams tool, in which different professors and students with developments in simulation and optimization related to the current COVID-19 problems could take part.

5 State of the art

The world has been strongly marked by diseases which have spread through the population and have claimed millions of lives. These are attributed to multiple origins, some of them animal in nature, where fighting them has not been an easy task. Consequently, epidemics such as the Black Death, HIV, Smallpox, among others, have generated major social and health problems, which required more advanced developments to stop their spread (René F. Najera, 2010). Multiple developments arose during the spread of each of these, seeking to find a vaccine that could be applied to the population in large quantities. Thus, scientific developments have promoted the control of diseases in different countries through mass vaccination processes, as in the case of Chen *et al.* (1987), where in the 20th century this process was carried out against Hepatitis B in Taiwan. The advances in science were not long in coming, resulting in international vaccination campaigns that were essential for the promotion of research and control of different types of diseases worldwide (Comstock, 1994).

As the population continues to increase and new diseases represent a greater affectation in the communities involved, it has been necessary to develop methods or techniques to enhance the different processes of mass vaccination that are carried out. Thus, at the beginning of the 21st century, optimization began to be a fundamental tool in the fight against emerging epidemics, as reported by Medlock & Galvani (2009), where developments in this area helped to define the optimal distribution of vaccines against influenza in the United States. Subsequently, integrating discrete event simulation models, new strategies known as drive-through vaccination were presented as a proposal to avoid new Influenza infections in the process of mass vaccination (Gupta *et al.*, 2013). Currently, as a result of the COVID-19 pandemic, a disease caused by the SARS-CoV-2 virus, Keske *et al.* (2020) shows the importance of prioritizing vaccination against respiratory viruses, where the control of propagation, vaccination of health personnel and investment in free health services are enhanced.

This pandemic that has swept the world to date has recorded more than 100 million confirmed cases, with a death toll of more than 2 million (World Health Organization, 2021). This situation has raised the level of urgency to end the virus, which is why different organizations and researchers throughout the world have put their interest in defining the most influential factors in the fight against it. Thus, Fitzpatrick & Galvani (2021) presents a study in which a characterization of different fundamental aspects in the spread of COVID-19 is made, comparing these in turn with other respiratory viruses, such as influenza. The previous work shows us the incidence that factors such as age and the probability of contact are of main interest. In turn, Yang *et al.* (2021) shows how vaccination processes in the world present very different dynamics between high, low and middle-income countries, thus directing its research to the optimal distribution of vaccines in countries belonging to the last two categories.

When it comes to designing and proposing new developments for COVID-19 mitigation around the world, optimization has been used as a fundamental tool in vaccine prioritization processes. These previous studies have considered different objectives, such as reducing the number of deaths, where Rahi & Sharma (2020) talks about the importance of considering strategies focused on high-risk individuals and thus having an effective control in the logistics of the vaccination processes. In addition, Bertsimas *et al.* (2020) conducts a study on the optimal distribution of vaccines in the United States to minimize deaths, using a dynamic simulation model and in turn developing a solution algorithm for the optimization problem, determining the prioritization of these doses in states with higher projection of cases and in high-risk populations. Rodríguez *et al.* (2020) tells us about mass vaccination processes with insufficient number of doses for a large part of the population, where vaccination of people with greater interaction represents in this case a decrease in deaths by mitigating the spread of the virus. On the other hand, objectives such as vaccination effectiveness have been considered, where Davies *et al.* (2020) evaluates school closure strategies in relation to the influence that young people have on the spread of the virus, thus confirming the importance of considering age in the vaccination process. In the same way, vaccination scenarios have been considered for which the risk of contagion at the moment of receiving the vaccine is high, for this reason Libotte *et al.* (2020) proposes multi-objective optimization models in which both the concentrations of the vaccine to be injected and the number of contagions in the process are minimized. Also, Matrajt *et al.* (2020) places special emphasis on mass vaccination of the population at greatest risk of contact, as this would slow down the spread of the virus. Another factor that has shown a great influence on the optimal use of vaccines refers to serological tests, which are antibody tests to determine whether people have had the virus in their bodies. Bubar *et al.* (2021) demonstrates, by means of a dynamic model, the contribution of the knowledge of the serostatus for an optimal administration of the population to be vaccinated. Additionally, Tran *et al.* (2021) shows how, from the real-time monitoring of the seropositive population, it is possible to make short-term distribution and control decisions on the vaccines to be administered in different territories of the United States. The above studies were fundamental in the planning of the governments when initiating their mass vaccination plans in each of the countries (Heath & Paun, 2020).

By February 2021, more than 30% of the inhabitants in Israel and the United Arab Emirates had begun to be vaccinated over the total population planned, while the other countries, especially middle and low-income countries, have the lowest proportions of vaccinated people (Heath & Paun, 2021). In the case of Colombia, it planned to start the mass vaccination process in February, in which it expects to receive a total of more than 34 million doses during the rest of the year (Minsalud, 2021b). As reported by Colprensa (2021), the country has acquired vaccines from five different companies. The first of them is Pfizer, with ten million doses, which seems to be 95% effective in preventing contracting the virus, according to preliminary studies, and which presents temperature conditions for its maintenance between -80 and -65 degrees Celsius. Ten million doses have also been acquired from Oxford and AstraZeneca, with an effectiveness slightly higher than 70% and withholding temperatures between 2 and 8 degrees Celsius. Likewise, the vaccines acquired from Janssen and Sinovac have the same temperature conditions mentioned above, of which nine and ten million doses have been acquired, respectively. Finally, Moderna will provide 10 million doses with an effectiveness of 94.1%, which must be stored at a temperature of -20 degrees Celsius.

In relation to the problems that the SARS-CoV-2 virus has presented in the population, the different studies that have been carried out in terms of mitigation and all the aforementioned developments for the implementation of mass vaccination campaigns, Colombia has designed an action plan to combat the virus (Minsalud, 2021d). This plan presents the stages of vaccination to be carried out until 2022, which are divided into five phases and where the main objective is to prioritize the population at risk of death and first-line health personnel, while reducing the spread of the virus in the national population. As reported by Minsalud (2020b), to meet these objectives, different vaccine distribution strategies have been defined in relation to thermal conditions and the need for medical personnel. Finally, these strategies seek to reach the objective of vaccinating 70% of the Colombian population and achieve herd immunity, where it will be possible to state that COVID-19 will no longer represent a latent problem in the country (Minsalud, 2021c).

6 Proposed methodology

In this research practice we expect to propose mathematical optimization models and the corresponding solution methods applied to mass vaccination in the Colombian context. In order to design such models and their solutions methods, regular weekly meetings are planned with the advisor in order to evaluate the progress of the project.

In order to achieve the objectives, this project has been divided into five phases as follows: The first phase will be dedicated to the study of the state of the art, evaluation of recent methods and become familiar with the literature on the problem. In this phase, it is proposed to review recent articles related to mass vaccination. The second phase will be devoted to define conceptual models, which include the specification of objective functions to be optimized, operational and logical constraints, and other assumptions related to case study. The development of mathematical models and their corresponding solution methods are the aim of the third phase. In the fourth phase we will verify and validate the proposed models. Finally, in the last phase we will report obtained results. Figure 1 presents a sketch of the five phases of the project.

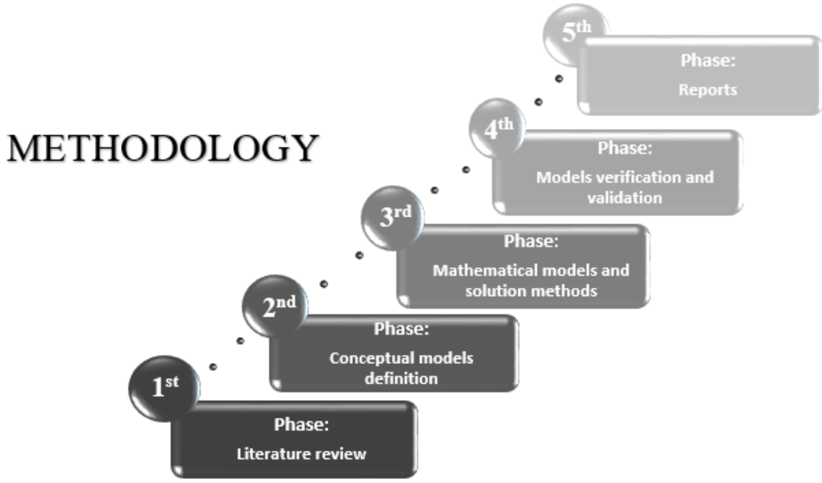

Figure 1: Methodology for the research process

7 Schedule

Table 1 summarizes the proposed schedule for this research practice.

Table 1: Schedule

Activity	*Weeks*																	
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
Literature review	■	■	■	■	■	■												
Conceptual models definition				■	■	■	■											
Mathematical models and solution methods						■	■	■	■	■	■	■						
Models verification and validation										■	■	■	■	■	■			
Reports															■	■	■	■

8 Budget

Universidad EAFIT provides data bases for the literature review, software licenses to implement the computer models and the required time of the tutor professor.

9 Intellectual property

According to the internal regulation on intellectual property within Universidad EAFIT, the results of this research practice are product of *Hamilton Smith Gómez Osorio* and *Juan Carlos Rivera*.

In case further products, beside academic articles, that could be generated from this work, the intellectual property distribution related to them will be directed under the current regulation of this matter determined by Universidad EAFIT (2017).

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