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Fuzzy Modelling on the Evolution of COVID-19 Epidemic under the Effects of Intervention Measures

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HIGHLIGHTS

- The fuzzy approach shows that intervention measures impede the spread of COVID-19.
- Even with the vaccine, the infection rate could be worse if safety measures are to be weakened.
- Results assists government decision making in order to minimize the spread of the pandemic.
- Physical distancing measures together with vaccines can contain the resurgences of the disease.

Abstract: This paper proposes to analyze how the intervention measures such as lockdown, partial lockdown and no-lockdown help to impede the spread of the severe outbreak of COVID-19 in Brazil. A p-fuzzy model, considering as input variables, the infected population and the intervention measures and as output variable the level of infestation, is proposed. The numerical results show that intervention measures play a crucial role in determining the success of COVID-19 eradication programs, while the population is being vaccinated in stages. Therefore, the model proposed assists government decision making in order to minimize the spread of the pandemic.

Keywords: COVID-19; Fuzzy model; population dynamics; measure interventions.

INTRODUCTION

The Coronavirus disease, named as COVID-19 pandemic, officially started in 2019 on the Asian continent and has spread widely. Since the emergence of this infectious disease, it has been subsequently span to every continent of the world, except Antarctica [1].

The spread of COVID-19 pandemic has motivated the development of studies and several research activities have been conducted for better understanding the origin, treatments and preventions of this virus [2]. According to Grzybowski, Silva and Rafikov (2020) [3], it has demanded a quick response from governments in terms of planning contingency efforts that include the imposition of social isolation measures. Even if one or more vaccines have high efficacy and uptake in the population, it will take at least several months for enough people to be vaccinated to confer herd immunity on a population basis [4]. For this reason and for prevent other diseases, the World Health Organization (WHO) [5] recommends that intervention measures, such as personal protective measures (hand hygiene, respiratory etiquette, mask wearing), environmental measures and physical distancing measures, are still necessary, even with the vaccine. Relaxing social distancing restrictions to the pre-pandemic level would lead to a new COVID-19 outbreak [6]. Atlani-Duault and coauthors (2021) [7] aim that we need a ``new COVID-19 social contract".

Biomathematical models have been proposed in the literature to describe the dynamics of the COVID-19 epidemic. Grzybowski, Silva and Rafikov (2020) [3] present an epidemic model specially tailored for the study of the COVID-19 epidemics. Authors present a case study with three prognostic scenarios for the first wave of the epidemic in the city of Manaus, Brazil. Results show that there are feasible control strategies that could substantially reduce the overload within reasonable time.

Ordinary differential equations are a powerful tool for mathematical modeling of population dynamics, since it is possible to choose the function that determines the variation in relation to the state of the variable. This fact limits the modeling of many phenomena, since the relationship between state variables and their variations is either subjective or partially known. This modeling is possible using p-fuzzy systems, which incorporate subjective information in both variables and variations and their relationships with variables, making the models more applicable and realistic [8].

According to Dhiman and Sharma (2020) [9], preventive measures for COVID-19 are crucial to control or to break down the chain of COVID-19. For this, authors proposed a fuzzy inference system to diagnose the COVID-19 by considering input factor like Ethanol, Atmospheric Temperature, Body Temperature, Breath Shortness, Cough and Cold and the output variable was divided into three linguistic values, denoting the severity level of the infected patients. More recently, a mediative fuzzy correlation technique based on the parameters for COVID-19 patients from different parts of India was developed in [10]. This technique provides the relation between the increments of COVID-19 positive patients in terms of the passage of increment with respect to time. The mathematical model can be used to find a fit or a contradictory model for any pandemic model.

A fuzzy approach about how intervention measures such as lockdown help to impede the extent of the severe outbreak of COVID-19 is presented in Stiegelmeier and Bressan (2021) [11]. The results of the model showed that intervention measures are fundamental to provide the success of COVID-19 eradication programs, in a no vaccine scenario, at the time when the article was written.

By using mathematical models to describe population dynamics and the behavior of epidemics, in the present study, a mathematical model using a discrete p-fuzzy system, is formulated, considering intervention measures for COVID-19 control. The input variables of the fuzzy system are the infected population and the intervention measures, which consists of social distancing such as lockdown, partial lockdown and no-lockdown. The output variable is the level of infestation. Numerical analysis is performed considering as simulation scenario. The proposed fuzzy model shows that intervention measures play a crucial role in COVID-19 eradication programs, while the population is being vaccinated in stages.

This paper is organized as follows: In the following section, we describe the concepts about p-fuzzy systems and the membership functions of the inputs (Infected population and Intervention measures) and the output (Level of infestation) variables, as well as the rules base used in the fuzzy system. In the Results and Discussion Section, numerical simulations and discussion of the results have been performed in order to analyze how the intervention measures can affect the dynamics of the virus. Lastly, the conclusions have been given in the last section.

MATERIAL AND METHODS

Let x the population density and $\Delta(x)$ the variation rate, in the iteration k. We consider a discrete p-fuzzy system as differences equation given by:

$$\begin{cases} x_{k+1} & = x_k + \Delta(x_k) \\ & x_0 \in \mathbb{R} \end{cases} \tag{1}$$

where $\Delta(x_k)$ is partly known and described by a fuzzy rule base.

The proposed model has two input variables: the infected-population density and the intervention measures, in a determine period of time, and one output: variation of population $\Delta(x, y)$. Suppose that such terms are modeled by fuzzy sets whose membership functions are obtained from a specialist.

We make the following assumptions:

1. The variation of infected populations $\Delta(x)$ depends on the population density of the specie, however, the increase (or decrease) of this rate will also be influenced by seasonality. That is, the population growth rate will change due to the intervention measures adopted.

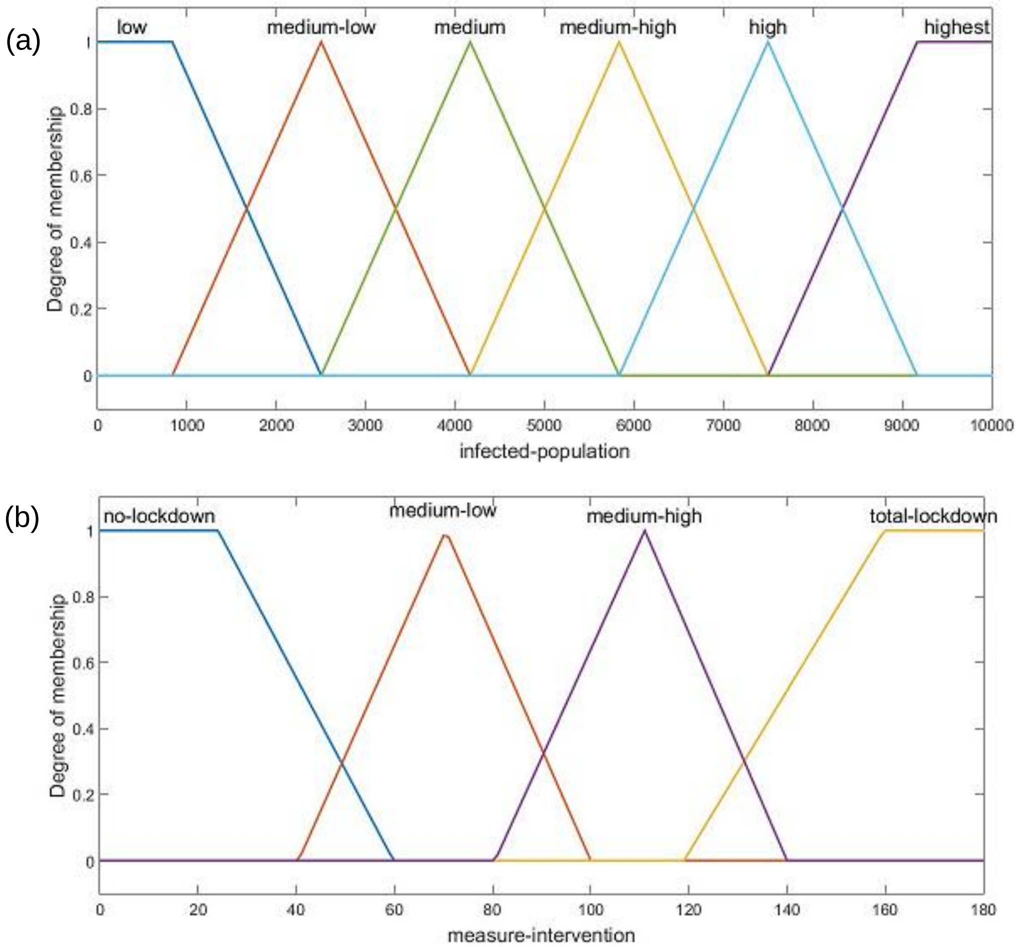
2. There will be greater growth if no intervention measures are taken and, when these are adopted, the birth rate decreases, reaching the point of having negative growth (only mortality) with a consequent decrease in the number of infected individuals.

3. The state variables, infected population density (x) and intervention measures (y), are represented by the set of linguistic variables:
   P_x = {low, medium low, medium, medium high, high and highest} and
   M_y = {No-lockdown, medium-low, medium-high and total-lockdown}.
   The input variable y will depend on the stage of the interactive system (k).

4. The output variation of infected populations $\Delta(x, y)$, is represented by L_Δ = {high-negative (H^-), medium-negative (M^-), low-negative (L^-), low-positive (L^+), medium-positive (M^+), high-positive (H^+)}.

5. We considered even if the infected population approaches to zero, they may increase again, provided the environment is favorable. That is, we considered that the virus has a latent state and when the condition is favorable, the virus returned.

Figure 1 shows the membership functions of the inputs (Infected population and Intervention measures) and the output (level of infestation) variables. It is important to highlight that [11] also proposed a fuzzy approach about the effects of intervention measures on the spread of COVID-19. The difference between [11] and this current paper is that the latter presents more linguistic classes in the input variables, better representing the problem under study, and a larger and more representative rule base.



(c)

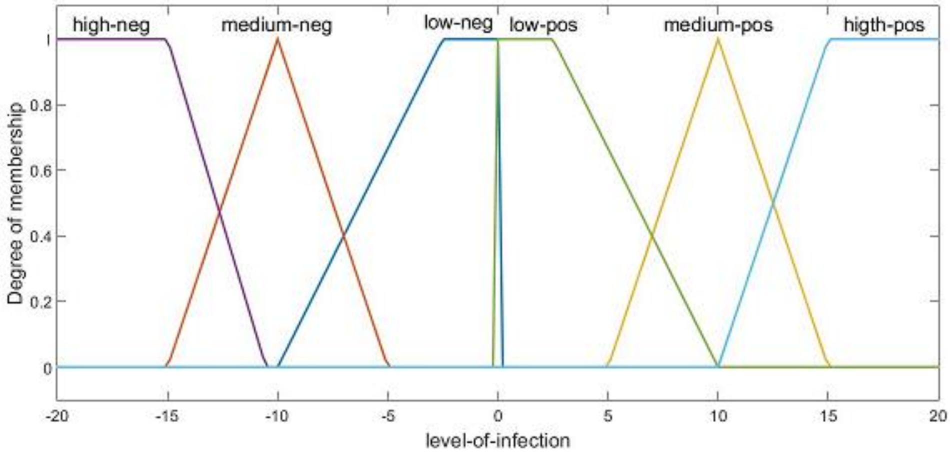


Figure 1. Input variables: (a) Infected population and (b) Intervention measures. Output variable: (c) Level of infestation

Following the assumptions (1)-(5), the system fuzzy rule base is given by 24 rules of the type:

"**IF** x is α_r **AND** y is β_r **THEN** $\Delta(x,y)$ is γ_r"

where $\alpha_r \in P_x$, $\beta_r \in M_y$ and $\$\gamma_r \in L_\Delta$ and $r \in \{1 \dots 24\}$ is the rule considered.

For example:

R1 - IF *(infected population)* is low AND (intervention measure) is no-lockdown, THEN the variation $\Delta(x,y)$ is medium-positive.

R2 - IF *(infected population)* is low AND (intervention measure) is Medium-low, THEN the variation $\Delta(x,y)$ is low-positive.

Table 1 shows the 24 linguistic rules constructed, the if-then rules base. We noticed that, if there is a favorable condition for the virus, that is, we active no-lockdown in the environment-action, so the population growth rate is highest; if the environment is always favorable, so the growth rate is positive, independent of the population size; and an unfavorable environment makes the population variation rate negative (mortality higher than birth).

Table 1. Rules base for the p-fuzzy model.

$x\backslash y$	No-lockdown	Medium-low	Medium-hight	Total-lockdown
Low	M+	L+	L+	L-
Medium low	H+	M+	L+	L-
Medium	H+	H+	L-	M-
Medium high	H+	M+	M-	M-
High	L-	M-	M-	H-
Highest	L-	M-	**H-**	H-

Therefore, the p-fuzzy model proposed is given by

$$\begin{cases} x_{k+1} = x_k + \Delta(x_k, y_k) \\ (x_0, y_0) \in \mathbb{R} \times [0,180] \to \mathbb{R} \end{cases} \quad (2)$$

where $\Delta(x,y)$ is given by the rules base shown in Table 1.

In Figure 1 (b), we can see that the measure-intervention has a dominion in $D(y) = [0,180]$, that is, $F: D \to [0,1]$. Thus, we considered a period of 180 iteration, where in the first 60 iterations, we obtain the membership degree in the no-lockdown set, and after that, in the medium-low and high lockdown set and, from 140 iterations, the total-lockdown linguistic variable is activated. In this paper, the time behavior of intervention measures as a cyclical system, since the virus behaves cyclically.

RESULTS

We evaluated the dynamics of the infected population considering the intervention measures like no-lockdown, medium low and medium high lockdown and total-lockdown. Here no-lockdown means when no intervention measure is adopted to contain the spread of the virus; medium low and medium high lockdown mean that average low or high measures were adopted by the countries and total-lockdown means social distancing measures taken to hinder the spread [12].

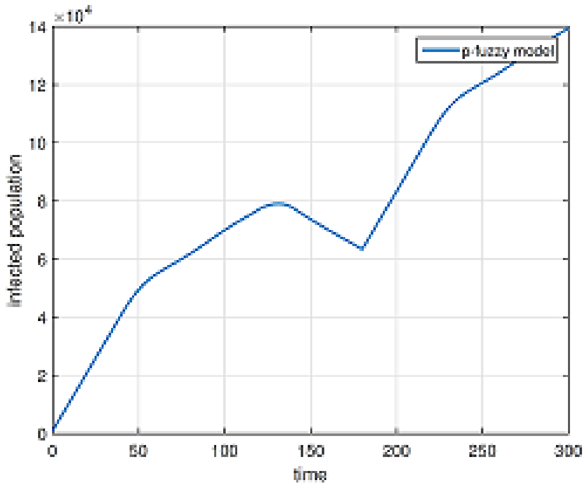
A scenario for the simulation was defined as follows. The initial condition of infected population and the period of time are fixed, $x_0 = 1000$ (daily cases), t = 300 iterations, respectively. The simulated was implemented using MATLAB software (www.mathworks.com). All experiments were run on a 2.4GHz Intel core i7 processor 8Gb of RAM memory and Windows 10 operating system.

The intervention measures were varied to active each linguist variable in set. The objective is to analyze how the intervention measures can affect the dynamics of the virus. Algorithm 1 describes the main code used to solve the fuzzy model used in the numeric simulation. The initial infected population, x_0, the intervention measure, y_0 and F the output of fuzzy rule base is given as input of the Algorithm 1.

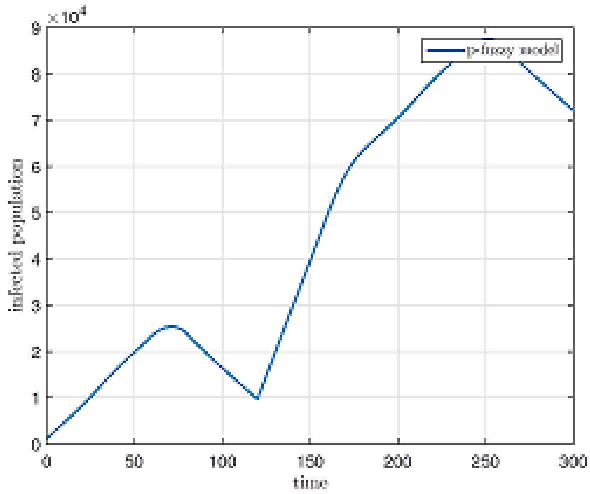
Algorithm 1 – The code used to solve the fuzzy model

Input: $\boldsymbol{x_0, y_0, F, K}$
Output: infected-population
Choose initial values: $\boldsymbol{x_0, y_0, K}$
for k from 1 to K do
    $\boldsymbol{\Delta(x_k, y_k) \longleftarrow F(x_k, y_k)}$
    $\boldsymbol{x_{k+1} = x_k + \Delta(x_k, y_k)}$
end
return $\boldsymbol{x_k}$ = infected-population

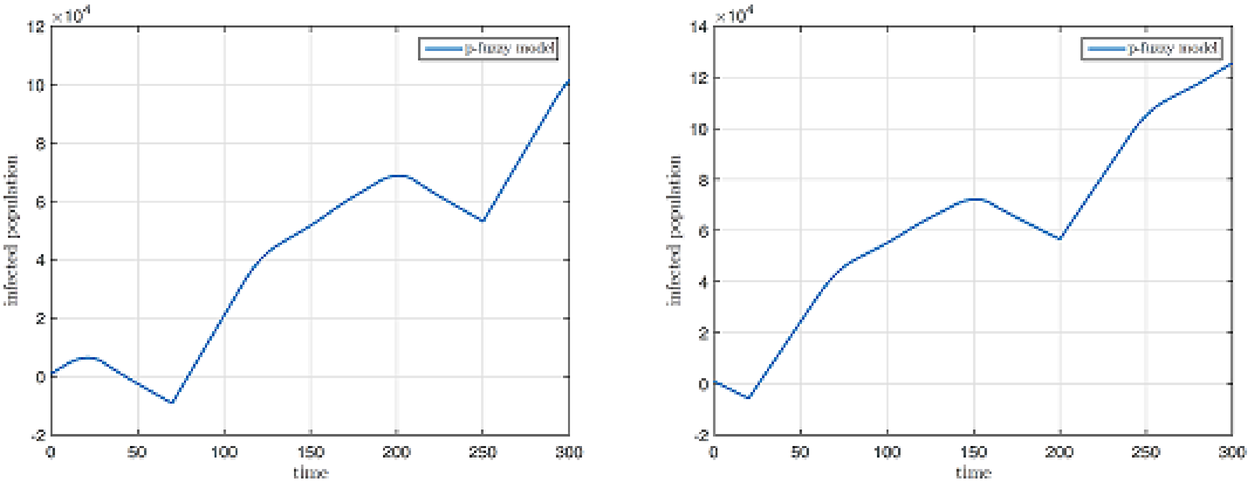
Figure 2 shows the dynamic of infected population varying the initial value of intervention measure. Figure 2 (a) illustrates the evaluated of the infected population considering the scenario where none intervention measure was adopted, so we active the linguist variable no-lockdown. We observe that the infected population grow faster in the begin period and decrease over the time but return to grow when no-lockdown is active again, representing the second wave of virus.



(a)



(b)



(c) (d)

Figure 2. P-fuzzy model solution with (a) $y_0 = 0$, no-lockdown active; (b) $y_0 = 60$, medium-low lockdown is active; (c) $y_0 = 110$, medium-high lockdown is active and (d) $y_0 = 160$, total-lockdown is active in set M_y.

In Figure 2 (b), the linguistic variable medium-low lockdown is active. We observe that there is a slowdown in the number of daily cases but a second wave, around 120 days, appear when the linguistic variable no-lockdown is active again.

Figure 2 (c) considers medium-high lockdown as active. So, we have a better scenario with number of daily cases lower. In addition, the model shows the third wave if no intervention measure was adopted around 250 days.

Figure 2 (d) illustrates the case where total-lockdown was active. We noticed that a drop occurs in the daily cases during the first days, it occurs due to the high level of intervention adopted (total-lockdown). However, if the population relaxed the measure, the virus returns at higher levels.

DISCUSSION

According to Acter and coauthors (2020) [2] and Rahaman and coauthors (2020) [12], the lockdown is the most efficient strategy to contain the coronavirus spread. Vaccination combined with physical distancing can stop the contamination, whereas a gradual vaccination process alone cannot contain resurgences [13].

Even though COVID-19 vaccines are becoming more available, safety measures, as lockdown, personal hygiene, and social distancing are still of pivotal importance in protecting personal and public health against COVID-19 [14]. Lockdowns and other restrictions give time for countries to reduce the incidence of disease and put in place robust, yet sustainable, measures to prevent and control transmission. Countries can consider policy alternatives and novel solutions developed by other countries and calibrate them according to their domestic circumstances and resources [15]. Therefore, even in the presence of the vaccine and the urgency of mass vaccination, the infection rate could be much worse if these safety measures are to be weakened.

The model proposed in this paper offers important insights in controlling the spread of COVID-19 using a p-fuzzy approach. The results of the p-fuzzy model were effective since we can understand that the intervention measures are the key to control the level of infected population. Thus, when fuzzy mathematical models are combined with the best intervention measure, the level of infected population can be mitigated.

CONCLUSION

This paper has suggested a fuzzy modeling for the evolution of infected population, focusing on the intervention measures and their effected in the increase of new cases of COVID-19.

The results showed that to consider medium-high lockdown helped to slow down the transmission rates of COVID-19 in the population, however the total lockdown is more effective, while the population has been vaccinated. In addition, the second wave of the pandemic, or the second cycle of the virus, has been more aggressive than the first one and the results presented in this paper demonstrate this fact.

In addition, mathematical models indicate that the only way to stop the spread of COVID-19 is the social isolation measures [3, 6, 13, 14, 16]. In this sense, these results converge with the results presented by the fuzzy model proposed in this paper. Physical distancing measures together with upcoming vaccines can contain the spread and the resurgences of the disease. The distancing make sure people are protected against COVID-19 till the pandemic ceases to pose a threat to personal or public health [14].

Therefore, the proposed fuzzy model contributes to minimize the risk of infection when social distancing was adopted. Results can assist government decision making in order to minimize the economic impacts caused by the pandemic and these prevention measures lead to a sudden decline in transmission rate of COVID-19 and turn out to be an effective strategy in containing the virus and saving lives.

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Conflicts of Interest: The authors declare no conflict of interest.

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