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Fuzzy logic for the management of vaccination during pandemics: a spread-rate-based approach

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ABSTRACT

Pandemics, such as coronavirus disease (COVID-19) are known to cause massive damage to the world's economic growth and their impacts are serious and influence across every aspect of social structure. The most inevitable factor in responding to the disaster of pandemics is the right management in terms of allocating a limited vaccine supply. The focus of this research work is to utilize a fuzzy logic inference system in the allocation of vaccine doses to the regional authorities by a central authority. The objective is obtained by designing a system based on fuzzy logic that considers the spread rate as the input to infer the vaccination rate of the local population. This system makes it possible for sufficient doses of vaccines to be allotted to the prioritized regions where the severity of the spread rate is a concern, and vaccines are not held up in regions where the severity of the spread rate is lesser. The designed system is verified using MATLAB software, which shows that this method can ensure an effective and efficient allocation of vaccination in the local regions and aid the fight against the disastrous spread of the disease.

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1. INTRODUCTION

Pandemics like coronavirus disease (COVID-19) have severely damaged global economies and caused widespread morbidity. They have created a global health crisis and the pandemics have put up cultural and geographical intolerance. The pandemics are far from over and are predicted to continue their crutches in the coming days [1]–[11]. Vaccination is the most effective tool for protecting people against pandemics [7]–[15]. Hence, the global efforts to develop vaccines to protect against pandemics have been unrivaled in the history of public health. As vaccine production scales up and new products are authorized, the allocation criteria will broaden until supply enables the widespread use of vaccines. The officials are facing an issue in the proper management in terms of optimal allocation of the vaccines to the different regions in pandemic situations. It will be a critical challenge to ensure that the allocation of vaccines is managed in a quick, effective, and unbiased way [14], [15].

The traditional method of distribution of vaccines by a central government or an authority to local state authorities is to allocate vaccine doses proportional to the population of the states and this method was recommended by the WHO during the COVID-19 pandemic [3]. A population-based distribution scheme seems to be expressing equality in terms of moral concern and may be considered to be politically tenable. However, it considers that equality implies treating different regions identically rather than equitably responding to their varying needs. Equally populous states can face different levels of spread of the pandemic. Providing aid merely based on population is unjust and against human reasoning. For example, it would be unjust and illogical to allocate antiretrovirals for HIV based on population, rather than on HIV cases [4]. In short, the schemes based on population have two disadvantages, the states having a severe spread rate may face a shortage of vaccines, resulting in super spreading and the states having a lesser spread rate may waste vaccines because of negligence to take vaccines due to pseudo security feeling. Hence, a fair and logical distribution of vaccines should respond to the pandemic's spread rate in different states, the spread rate of the region has to be prioritized to avoid widespread or super spread in those states with a severe spread rate [12].

Not much research work is available in the literature on the direction of incorporating the spread rate in the decision-making of the distribution of vaccines. One approach considering the spread rate was proposed in [4], in which the fair priority model was developed. This model considers the premise that the regions affected by highly severe spread rates are given top priority, but all regions have to be ultimately allocated adequate doses of vaccines to break the chain of spread. In this approach, the estimation of vaccine allocation demands the model integration with data and forecasts based on experience. However, empirical uncertainties make this approach very difficult or almost impractical to implement [4].

In this research effort, an algorithm is developed, one that considers the spread rate, which is characterized by two quantities, the number of confirmed cases and the rate at which the confirmed cases vary for ascertaining the rate of vaccination. Nevertheless, there are no hard and fast rules or precise analytical models that define the functional relation that associates the inputs to the output, but some experience-based approximate rules are available. Fuzzy logic is a prominent soft computing tool that embeds structured experience-based rules into computer algorithms, and it incorporates approximate human reasoning modes in computer algorithms [16]–[23]. Hence, we propose an implication system utilizing fuzzy logic that considers the number of confirmed cases and the rate at which confirmed cases vary for ascertaining the ratio of scarce vaccine supply to be allocated to various regions, and therefore to determine the vaccination effort of different regions. This novel scheme ensures that sufficient doses of vaccines are allotted to the states on priority where spread rates are higher, and vaccines are not wasted in states where the spread rates are lower and ensures effective and efficient distribution of the available vaccine doses to the states and enhance the fight against pandemics.

The rest of this paper is structured in the following sections. Section 2 describes the method of developing a fuzzy logic algorithm that considers the severity of the spread rate to ascertain the vaccination effort. Section 3 presents the results and deliberations that establish the efficacy of the proposed technique. Finally, the conclusions with relevant discussions and findings are presented in section 4.

2. METHOD

The input quantities, the number of confirmed cases, and the rate at which confirmed cases vary are scaled into the normal range of [0,1] by appropriate scaling factors. The normalized number of confirmed cases and the normalized rate at which confirmed cases vary are the inputs to the fuzzy logic system. The output of the system is the vaccination effort, normalized in the range [0,1].

2.1. Fuzzification

The normalized variables, number of confirmed cases, and the rate at which confirmed cases vary are applied to the fuzzification block that uses triangular membership functions of the knowledge base which are given respectively in Figures 1 and 2. The fuzzy linguistic variables of the input "number of confirmed cases" are very low (VL), low (L), medium (M), high (H), and very high (VH) and those of the input "rate of change of number of active cases" are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB). The fuzzy sets of the output "vaccination rate" are VL, L, M, H, and VH as shown in Figure 3.

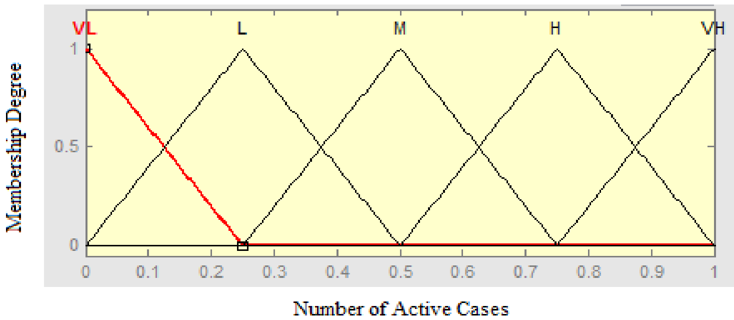

Figure 1. Knowledge base: number of confirmed cases

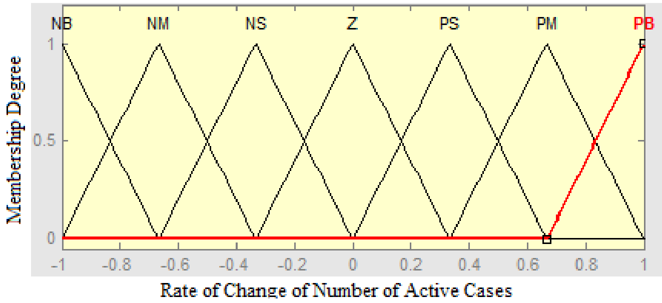

Figure 2. Knowledge base: the rate at which confirmed cases vary

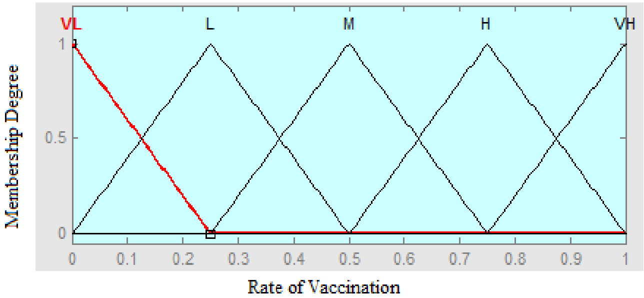

Figure 3. Knowledge base: vaccination rate

2.2. Rule base

The rule base of the proposed method for inferring vaccination based on the spread rate is designed using human experience-based approximate rules. The spread rate is determined by the number of confirmed cases and the rate at which confirmed cases vary. The rules are given in Table 1. The rules are designed such that the vaccination effort is higher if the severity of the spread rate is higher and the vaccination effort is lower if the severity of the spread rate is lower. The fuzzy surface showing the relationship between inputs and output relationship is as in Figure 4.

Table 1. Rule base

Rate of changeof active cases	Active cases				
	VL	L	M	H	VH
NB	VL	VL	VL	L	M
NM	VL	VL	L	M	H
NS	VL	L	M	H	VH
Z	L	M	H	VH	VH
PS	M	H	VH	VH	VH
PM	H	VH	VH	VH	VH
PB	VH	VH	VH	VH	VH

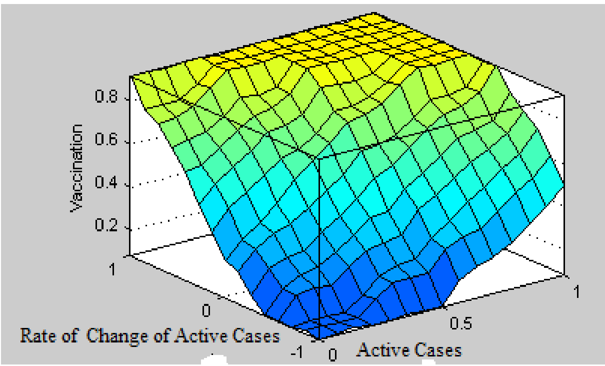

Figure 4. Relationship between inputs and output

2.3. Fuzzy inference

The proposed algorithm uses the Mamdani Interference algorithm. In the Mamdani algorithm, the "if" part of every rule is a connected statement involving fuzzy sets of input variables using the "and" logic and the "then" part is a fuzzy set of the output variable [22]–[26]. For instance, in this system, rules are of the form "if the number of confirmed cases is VB and the rate of vary of the number of confirmed cases is PH, then the vaccination rate is VH". As the input fuzzy sets are connected by the "and" logic, the operator "min" is operated on the membership values of two inputs to find the truth value of the corresponding rule, which is applied to the output fuzzy variable "VB". This procedure gives fuzzy outputs for all the rules, and they are then combined by applying the "max" operator on the fuzzy outputs to obtain a final fuzzy output.

2.4. Defuzzification

The final output of the fuzzy implication is defuzzified using the center of gravity scheme, in which the center of gravity of the fuzzy output is calculated using (1). The center of gravity scheme is preferred in this technique as it produces highly smooth and precise output [22], [26].

$$z^* = \frac{\int \mu_C(z).z\,dz}{\int \mu_C(z)\,dz} \quad (1)$$

where z^* represents the defuzzified value of the output z, $\int \mu_C(z)$ holds the membership function of the aggregated fuzzy output.

3. RESULTS AND DISCUSSION

For studying the efficacy of the proposed algorithm, consider the case of allocating vaccines to six regions: region 1, region 2, region 3, region 4, region 5, and region 6, where the normalized value of the number of confirmed cases and normalized value of the rate at which confirmed cases vary are as shown in Table 2. The computation of the proposed algorithm is implemented using the fuzzy logic toolbox of MATLAB, the results are shown in Figure 5 to Figure 10. The rates of vaccination in various regions inferred by the proposed algorithm are tabulated in Table 3.

Table 2. Input parameters

Region	Normalized value of the number of confirmed cases	Normalized value of rate at which confirmed cases vary
Region 1	1	1
Region 2	1	-1
Region 3	0.5	0.5
Region 4	0.5	-0.5
Region 5	0.1	0.5
Region 6	0.1	-0.5

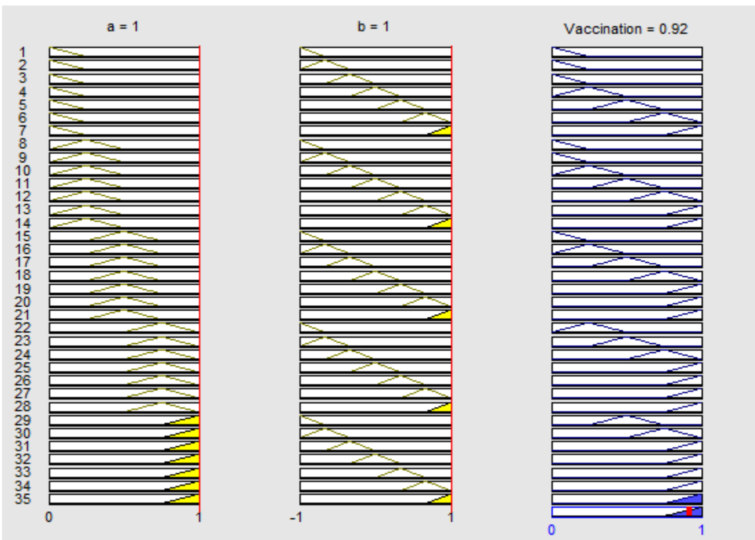

Figure 5. Inference of region 1

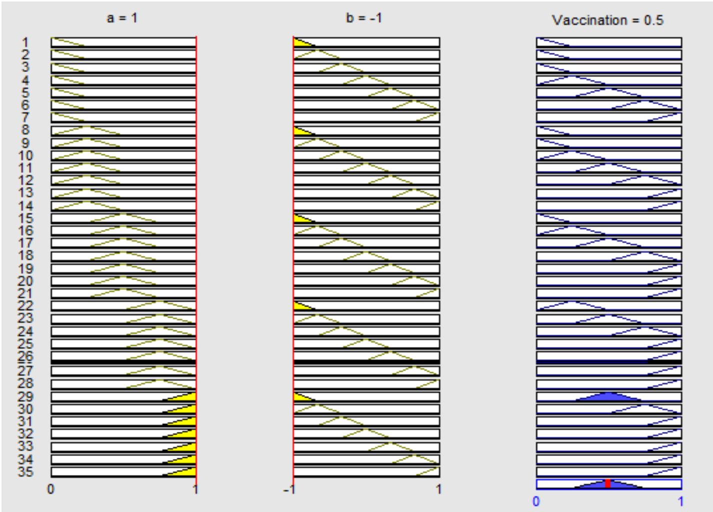

Figure 6. Inference of region 2

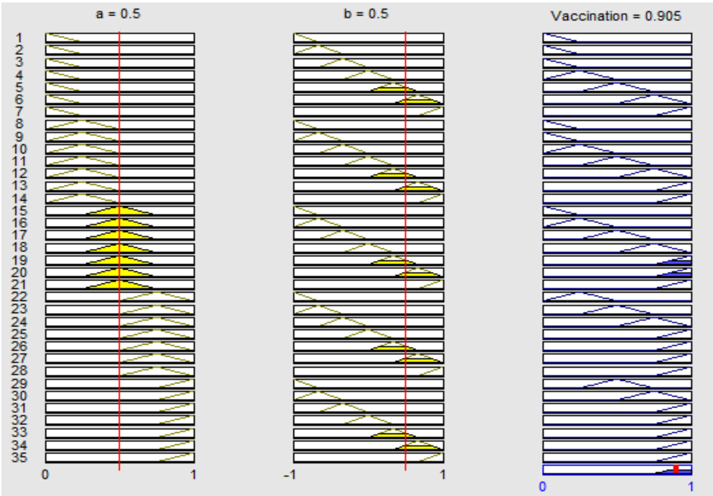

Figure 7. Inference of region 3

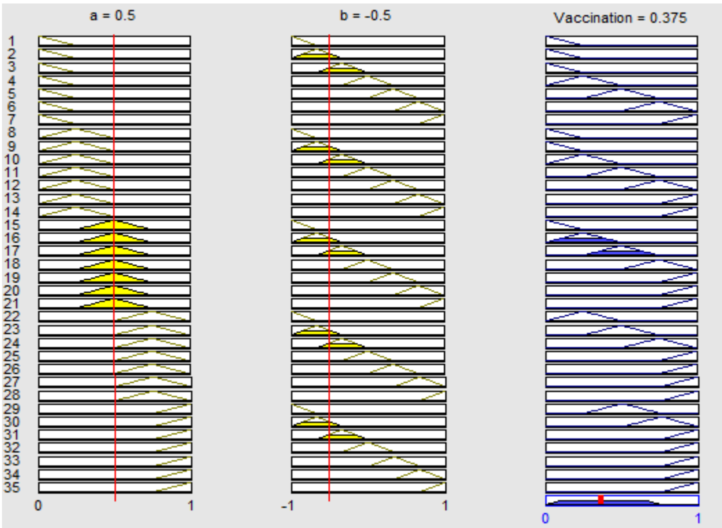

Figure 8. Inference of region 4

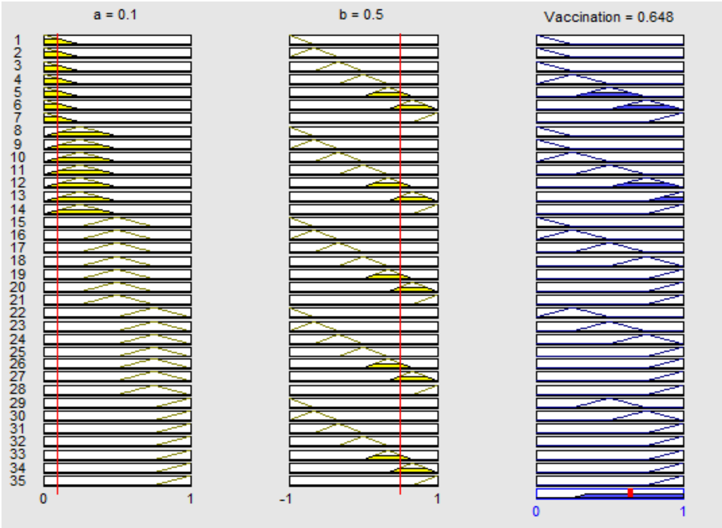

Figure 9. Inference of region 5

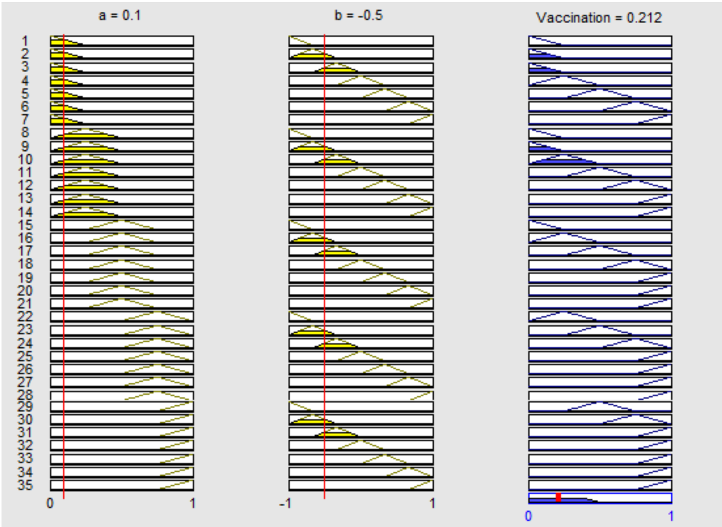

Figure 10. Inference of region 6

Table 3. Vaccination effort

Region	Normalized value of vaccination rate
Region 1	0.92
Region 2	0.5
Region 3	0.905
Region 4	0.375
Region 5	0.648
Region 6	0.212

In region 1, where normalized values of number of confirmed cases and the rate at which confirmed cases vary are respectively 1 and 1 (both are higher), the vaccination rate is 0.92 (higher). In region 2, where normalized values of the number of confirmed cases and the rate at which confirmed cases vary are respectively 1 (higher) and -1 (the severity is falling at a higher rate), the vaccination rate is 0.5 (medium). In region 3, where normalized values of the number of confirmed cases and the rate at which confirmed cases vary are respectively 0.5 (medium) and 0.5 (severity is rising at the medium rate), the vaccination rate is 0.905 (higher). In region 4, where normalized values of the number of confirmed cases and the rate at which confirmed cases vary are respectively 0.5 (medium) and -0.5 (the severity is falling at the medium rate), the vaccination rate is

0.375 (lower). In region 5, where normalized values of number of confirmed cases and the rate at which confirmed cases vary respectively 0.1 (lower) and 0.5 (the severity is rising at the medium rate), the vaccination rate is 0.648 (medium). In region 6, where normalized values of the number of confirmed cases and the rate at which confirmed cases vary are respectively 0.1 (lower) and -0.5 (the severity is falling at the medium rate), the vaccination rate is 0.212 (lower). The computation results prove that the proposed fuzzy algorithm considers the spread rate for ascertaining the vaccination rate allocated to different regions. This inference system makes sure that adequate doses of vaccines are allotted to the prioritized regions where the severity of spread rates is complex, and vaccines are not held up in regions where the spread rate is not that severe. The proposed allocation system enables proper allocation of the existing vaccine supply and hence an effectual vaccination, and aid in containing the disastrous spread of pandemics.

The proposed allocation scheme has the limitation that the population of the region is not at all a factor in deciding the vaccination rate, and it fails to consider the natural concern that all regions should be ultimately allocated adequate vaccine doses to break the chain of transmission. In near future work, we propose to develop a fuzzy algorithm based on both the spread rate and population to infer the vaccination rate. The objective is to ensure that adequate doses of vaccines are allocated to the prioritized regions where the severity of the spread rate is higher and vaccines are not held up in regions where the severity is lower, simultaneously, all regions are ultimately allocated adequate vaccine doses to break the chain of transmission.

4. CONCLUSION

In this paper, a fuzzy logic algorithm for the right management of vaccination by conjecturing the allocation of the constrained vaccine doses available from a central authority to regional authorities. The proposed algorithm is based on a fuzzy inference system that considers the severity of the spread of the disease to compute the vaccine doses to be distributed to various regions of a central authority. This scheme makes sure that adequate doses of vaccines are allocated to the prioritized regions in which the severity of the transmission of the disease is higher and vaccines are not held up in regions in which the severity is lesser. The proposed algorithm is evaluated using the fuzzy logic toolbox of MATLAB. The results imply that the proposed algorithm ensures the appropriate distribution of the available vaccine supply and hence an effectual vaccination of all the regions and boosts the fight against the disastrous transmission of the pandemic disease.

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