A Fuzzy Logic Scheme Based on Population and Spread Rate for the Management of Vaccination during Pandemics

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Research Article

Keywords: Fuzzy logic, Mamdani inference, Vaccination, Population, Spread rate, MATLAB

Posted Date: December 12th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3741920/v1

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Additional Declarations: The authors declare no competing interests.
Abstract

The pandemics like COVID-19 cause a massive shock to the global economy and its impacts are huge and endure across all domains of life. Effectively managing the limited vaccine supply is crucial in the fight against pandemics. A central issue in the management of pandemic vaccination is the allocation of vaccines from the central government to state authorities. The objective of this research was to make use of a fuzzy logic scheme for the management of vaccination to the local state authorities by a central Government based on population and spread rate. The proposed scheme utilizes a fuzzy logic inference system taking into account on population and spread rate to infer the vaccination rate. This scheme is in contrast to conventional approaches that often consider either a state's population or spread rate as the sole basis for vaccine allocation. The Covid-19 data of 6 southern states of India during the first week of October 2020 collected from the database maintained by the Ministry of Health and Family Welfare of Government of India was used for the verification of the proposed scheme. The proposed scheme was implemented using MATLAB/SIMULINK software and compared with the conventional schemes, one based on population and another based on spread rate. The results show that the proposed scheme ensures that sufficient doses of vaccines are allotted to the states on priority where spread rate is more and vaccines are not wasted in states where spread rate is less. At the same time, all states are eventually allotted sufficient vaccine doses to halt transmission. The proposed scheme ensures that sufficient vaccines are distributed in a quick, effective and unbiased way, and enhances the fight against pandemics.

1 Introduction

Pandemics like COVID-19 have caused wide ranging morbidity and divested economies worldwide [1]. They created global health crisis and the pandemics have caused cultural and geographical intolerances. The pandemics are far from over and it is anticipated that the pandemics will continue the crutches in the coming days [2–10]. Vaccines are the one of the most effective and efficient tools for protecting people against pandemics [7–14]. Hence, the global efforts to develop vaccines to protect against pandemics have been unrivalled 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 of delivery of the vaccines to different locations in pandemic situations. It will be a critical challenge to ensure that sufficient vaccines are distributed in a quick, effective and unbiased way [13–14].

The traditional method of distribution of vaccines by a central government or an authority is to allocate vaccine doses proportional to population of the local authorities (states) and this method was recommended by the WHO during the COVID-19 pandemic [2]. A population based distribution scheme looks to be expressing equal moral concern and may be considered to be politically tenable. However, it assumes that equality requires treating different states 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 the human reasoning. For example, it
would be unjust and illogical to allocate antiretroviral for HIV on the basis of population, rather than on HIV cases [3]. In short, this scheme has two disadvantages. The states having a smaller population receive fewer vaccine doses and may face shortage of vaccines, resulting in super spreading if those states have a higher spread rate. Similarly, the states having a higher population receive more vaccine doses, and may waste vaccines because of negligence to take vaccines due to pseudo security feeling caused by a lower spread rate. Hence, a fair and logical distribution of vaccines should respond to the pandemic's differential severity in different states, the spread rate of the states have to be considered to avoid widespread or super spread in those states with a higher spread rate [13–16].

Not much research has been done in the direction of incorporating spread rate in the decision making of the distribution of vaccines. One approach considering the severity was proposed in [3], in which the Fair Priority Model was developed. This model takes into account the premise that the states with higher transmission rates are prioritized [3]. In this approach, the spread rate is the sole factor in deciding the vaccination rate and hence it has a disadvantage that the population of the state is not at all considered in deciding the vaccination rate, and it fails to address the natural human reasoning that all states should be eventually allotted sufficient vaccine doses to halt transmission. For example, if spread of a state is decreasing at a higher rate, this method infers a lower vaccination rate even if the population is very high. This may result in uncontrolled spread in some populous states with a lesser spread rate and they may become hotspots sooner or later [5]. Also, if spread of a state is increasing at a higher rate, the inference will be a higher vaccination rate even if population of that state is very small. This may waste vaccines due to excess supply for a smaller population. This disadvantage makes this method against the human reasoning and unjust.

In this paper, we propose a scheme which takes into consideration both population and spread rate, spread rate being represented by the weekly average of the rate of change of number of active cases in the states, to decide the vaccination rate. The vaccination rate represents the number of doses to be allotted to the states. However, there are no strict and hard rules or exact mathematical models to define the relationship between inputs-population and spread rate, and the output vaccination rate, as they are fuzzy, but there are some approximate rules based on human reasoning. Fuzzy logic is an apt tool for embedding structured human reasoning into workable algorithms and supports a model for human reasoning modes that are approximate [17–27]. Hence, we propose a fuzzy logic based inference system which takes into account population and spread rate for inferring the vaccination rate. This novel scheme ensures that sufficient doses of vaccines are allotted to the states on priority where spread rate is higher and vaccines are not wasted in states where spread rate is lower. Also, all states are eventually allotted sufficient vaccine doses to halt transmission. This ensures an effective and efficient distribution of the available vaccine doses to the states and enhances the fight against pandemics.

The remainder of this paper is organized as follows. Section 2 presents fuzzy logic scheme based on population and spread rate for inferring vaccination rate. Section 3 presents results and discussion. Section 4 presents conclusions.
2 Fuzzy Logic Scheme Based on Population and Spread Rate for Inferring Vaccination Rate

The two input variables, population and spread rate (weekly average of the rate of change of number of active cases) are normalized into the range [0,1] by suitable input scaling factors. The scaling factor of population is the population of the most populous state and scaling factor of spread rate is the maximum of the absolute value of spread rate of all the states. The normalized population and the normalized spread rate are the inputs to the fuzzy interface system. The vaccination rate, in the range [0,1] is the output.

2.1 Fuzzification

The normalized inputs, population and spread rate are fuzzified using triangular membership functions as shown in Fig. 1 and Fig. 2 respectively. The fuzzy sets of the input Population ‘P’ are VL (Very Low), L (Low), M (Medium), H (High) and VH (Very High) and those of the input Spread Rate ‘S’ are NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). The fuzzy sets of the output Vaccination Rate ‘V’ are VL (Very Low), L (Low), M (Medium), H (High) and VH (Very High) as shown in Fig. 3.

2.2 Rule Base

The rule base of fuzzy inference system developed using the approximate human reasoning is given in the Table 1. The relation between inputs and output is shown in Fig. 4.

<table>
<thead>
<tr>
<th>Population Spread Rate</th>
<th>VL</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
</tr>
<tr>
<td>NM</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>L</td>
</tr>
<tr>
<td>NS</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>Z</td>
<td>VL</td>
<td>VL</td>
<td>L</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>PS</td>
<td>VL</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>VH</td>
</tr>
<tr>
<td>PM</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>VH</td>
<td>VH</td>
</tr>
<tr>
<td>PB</td>
<td>M</td>
<td>H</td>
<td>VH</td>
<td>VH</td>
<td>VH</td>
</tr>
</tbody>
</table>

2.3 Fuzzy Inference
Mamdani interference scheme is proposed for this system. In Mamdani inference scheme, the antecedent part of each rule is a compound statement using connective “and” and the consequent part is represented by a fuzzy set [23]. For example, in this system, one rule is of the form “If population is VH and spread rate is PB, then vaccination rate is VH”. As the connective is between inputs is “and” operator, the fuzzy operator “min” is applied for the membership values to obtain truth value of the rule. This truth value is then applied to the output fuzzy set “PB”. The fuzzy outputs corresponding to different rules are then aggregated using max operator [24–27].

### 2.4 Defuzzification

The aggregated fuzzy output is defuzzified using centroid method, the centroid defuzzification computes the centroid of the aggregated fuzzy output using Eq. (1). The centroid method is utilized because it generates highly precise and smooth output [23].

\[
z^* = \frac{\int \mu_C(z) \cdot zdz}{\int \mu_C(z) dz}
\]

1

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

### 3 Results and Discussion

For the verification of the proposed scheme, the population data collected from database maintained by Reserve Bank of India and the Covid-19 data of first week of October 2020 collected from the database maintained by the Ministry of Health and Family Welfare of Government of India were used. The vaccination rate of different states computed by the proposed fuzzy logic-based inference system are shown in Fig. 5 to Fig. 10. The comparison of vaccination rate inferred using different methods is presented in Table 2.
Table 2
Comparison of Vaccination Rate

<table>
<thead>
<tr>
<th>State</th>
<th>Vaccination Rate</th>
<th>Scheme based on Population</th>
<th>Scheme based on Spread Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proposed Scheme</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kerala</td>
<td>0.856</td>
<td>0.463</td>
<td>1</td>
</tr>
<tr>
<td>Tamil Nadu</td>
<td>0.917</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Karnataka</td>
<td>0.279</td>
<td>0.847</td>
<td>0.2</td>
</tr>
<tr>
<td>Telangana</td>
<td>0.333</td>
<td>0.485</td>
<td>0.55</td>
</tr>
<tr>
<td>Andhra Pradesh</td>
<td>0.276</td>
<td>0.687</td>
<td>0.35</td>
</tr>
<tr>
<td>Puducherry</td>
<td>0.0863</td>
<td>0.017</td>
<td>0.45</td>
</tr>
</tbody>
</table>

In the state of Kerala, where the population is relatively medium with a normalized value of 0.463 and the spread is increasing at a relatively higher rate with a normalized value of 1, a relatively higher vaccination rate of 0.856 is inferred by the proposed scheme, whereas the conventional scheme based on population infers a medium vaccination rate of 0.463 as the population of Kerala is medium and, the scheme based on spread rate infers a relatively very higher rate of 1 as the spread is increasing at the maximum rate. In the state of Tamil Nadu, where the population is very high with a normalized value of 1 and the spread is increasing at a relatively smaller rate with a normalized value of 0.4, a relatively very higher vaccination rate of 0.917 is inferred by the proposed scheme, whereas the conventional scheme based on population infers a very higher vaccination rate of 1 as the population of Tamil Nadu is the highest among six states, and the scheme based on spread rate infers a relatively medium rate of 0.7 as the spread is increasing at a medium rate. In the state of Karnataka, where the normalized population is relatively higher at 0.847 and the spread is decreasing at a relatively medium rate of -0.6, the proposed scheme infers a relatively lower vaccination rate of 0.279, whereas the conventional scheme based on population infers a relatively higher vaccination rate of 0.847 as the population of Karnataka is relatively higher and, the scheme based on spread rate infers a relatively lower rate of 0.2 as the spread is decreasing at a relatively medium rate. In the state of Telangana, where the normalized population is relatively medium at 0.485 and spread is increasing at a relatively lower rate of 0.1, the proposed scheme infers a relatively lower vaccination rate of 0.333, whereas the conventional scheme based on population infers a relatively medium vaccination rate of 0.485 as the population of Telangana is relatively medium and, the scheme based on spread rate infers a relatively medium rate of 0.55 as the spread increasing at a relatively lower rate. In the state of Andhra Pradesh, where the normalized population is relatively higher at 0.687 and spread is decreasing at a relatively lower rate of -0.3, the proposed scheme infers a relatively lower vaccination rate of 0.276, whereas the conventional scheme based on population infers a relatively higher vaccination rate of 0.687 as the population of Andhra Pradesh is relatively higher and, the scheme based on spread rate infers a relatively lower rate of 0.35 as the spread is decreasing at a relatively lower
rate. In the state of Puducherry, where the normalized population is relatively very lower at 0.017 and spread is decreasing at a relatively lower rate of -0.1, the proposed scheme infers a relatively very lower vaccination rate of 0.0863, whereas the conventional scheme based on population infers a relatively very lower vaccination rate of 0.017 as the population of Puducherry is relatively very lower and, the scheme based on spread rate infers a medium rate of 0.45 as the spread is decreasing at a relatively lower rate.

The results show that the proposed fuzzy logic based inference system takes into account both population and spread rate for inferring the vaccination rate allocated to the local authorities of different states. This novel scheme ensures that sufficient doses of vaccines are allotted to the states on priority where spread rate is more and vaccines are not wasted in states where spread rate is less. At the same time, all states are eventually allotted sufficient vaccine doses to halt transmission. This ensures an effective and efficient distribution of the available vaccine doses to the states and enhances the fight against pandemics.

4 Conclusions

In this paper, a fuzzy logic based scheme is proposed for the management of vaccination by inferring the vaccination rate for allocating the limited vaccine doses available from a central Government to state authorities. The proposed fuzzy logic based inference system takes into account population and spread rate for inferring the proportion of available vaccine doses to be allocated to the states. Hence, in the proposed scheme, vaccination is prioritized for states with higher spread rate and ensures that vaccines are not held up in states where the severity is lower. At the same time, all states are eventually allotted sufficient vaccine doses to halt transmission. The proposed scheme is computed using fuzzy logic toolbox of MATLAB. The results show that the proposed scheme ensures proper distribution of the available vaccine doses and hence an effective, efficient vaccination of the states, and enhances the fight against pandemics.

Declarations

Funding

The author has no relevant financial or non-financial interests to disclose. Moreover, the author did not receive support from any organization for the submitted work.

Conflict of interest

The author declare that he has no conflict of interest.

References

1. Mona Al–Amin, Kate Li, Jennifer Hefner and Md Nazmul Islam, "Were hospitals with sustained high performance more successful at reducing mortality during the pandemic's second wave?,” Health


**Figures**

![Figure 1](image1)

**Figure 1**

Input membership functions of population

![Figure 2](image2)

**Figure 2**

Input membership functions of spread rate
Figure 3

Output membership functions of vaccination rate

Figure 4

The relationship between inputs and Output
Figure 5

Fuzzy inference of Kerala

Figure 6
Fuzzy inference of Tamil Nadu

Figure 7

Fuzzy inference of Karnataka
Figure 8

Fuzzy inference of Telangana
Figure 9

Fuzzy inference of Andhra Pradesh

Figure 10

Fuzzy inference of Puducherry