Title: Using Mamdani Type 1 Fuzzy Logic to Evaluate and Enhance Diagnosis of Respiratory Infections in Clinical Settings.

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AIM: This research aims to build a type 1 Mamdani fuzzy system to infer the probability of severity of respiratory tract infections in humans, deduce the most efficient membership function combination for the most precise result, test the system in clinical settings, and recommendations for further works.

Keywords:

Infection, Clinical case, Membership functions, Wheezing, Cough, defuzzification,

Outline

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DIAGNOSING RESPIRATORY INFECTIONS

Respiratory infections, including bronchitis, pneumonia, and lung abscesses can be a result of bacteria or viruses. The level of respiratory infection usually ranges from acute to chronic, and for both cases classified into upper respiratory and lower respiratory tract infections, the acute respiratory infection affects the function of the lungs, and symptoms like wheezing, coughing, or difficulty in breathing are experienced by the patient (Simoes et al, 2006).

During clinical diagnosis of respiratory infections, some of the Initial symptoms are running, stuffy nose, and sneezing, usually without fever in some cases, although burning fevers are evident in cases like Pneumonia, or children with upper respiratory tract infection signs of difficulty breathing, muffled speech or drooling can also be experienced.

In 2016 Hector Rodriguez et al. conducted a study to assign a score to the severity of acute respiratory infection, this score was derived from a physical examination of the ability to breathe, this experiment was conducted on infants who were hospitalized he divided the severity into 4 groups, it was acute if the respiratory rate was normal and the heart rate was regular, the second group had mild breathing problems and noticed by retraction of the intercoastal muscles, a medium group that needed help breathing and the last the acute which had a higher respiratory rate with wheezing and also a characteristic contraction of the intercoastal muscle, in this research this expert linguistic variables will be used to quantify the level of respiratory infections for the fuzzy inference system.

MAMDANI TYPE ONE FUZZY INFERENCE SYSTEMS (FIS)

Fuzzy inference systems is a computational method that interprets values of input based on sets of rules and outputs a result, it uses the fuzzy logic approach to assign membership values to a set, and the membership functions determine the membership level of elements in a given set.

FIS systems have great potential for assisting healthcare diagnosis, especially in regions fronting a shortage of medical practitioners, to enhance this diagnostic precision, various algorithms including FIS, are actively researched, this advancement shows a promising future in the healthcare industry (J.B. Awotunde, 2014).

Our goal is to develop a type I Mamdani fuzzy logic system we will be using the diagnostic decisions made by the medical experts and the linguistic variables used on the system will reflect the perceptions of these experts.

METHODOLOGY

I collected data from several medical sources, by querying journals using words like scoring respiratory infections, and clinical diagnoses to understand the linguistic variables and determination of the fuzzy input. We will be using 3 fuzzy Inputs namely, Temperature, cough, and shortness of breath (Wheezing)., as these are the major signs that can be determined via physical examination (Hector Rodriguez et al., 2016).

I will also be using MATLAB environment for building this Fuzzy inference system.

Membership Functions (MF)

A membership function is a function that signifies the degree of membership of a crisp set, the degree of membership is signified as a range of 0 – 1, with 0 signifying no degree of membership and 1 that it's a complete member of that set. This enables us to solve human problems based on experience, and Linguistic expressions.

Mathematically, for every member of the universal set X, set A is the membership value of an element in the universal set. Where the membership value is values between 0 and 1.

$$A = (\, x,\ \mu A(x)\,)\,|\, x\ \in\ X$$

Structure of a membership function

The **core** of the membership function represents sets of elements that have a membership degree of 1, the **boundary** is a group of elements that have a non-membership degree of 1 and a membership degree above 0. This work will deal with the 4 most popular types of membership functions which are.

1. Triangular MFs (trimf): It assumes the core to be a single point and has the shape of a triangle.
2. Trapezoidal MFs (trapmf): It takes a range of values as the core of the MF.
3. Gaussian MFs (gaussmf): Characterized by its smooth curve around the core and smooth slope down the boundaries.
4. Sigmoid MFs (sigmf): Has a smooth S-shaped curve that smoothly transitions from 0 to 1.

FUZZY INPUTS

After carefully sorting out our data, we need to fuzzify the crisp sets by assigning membership values to them.

Cough: Cough is one of the most common initial signs of respiratory infection, it is a reflex action that happens intending to remove toxins from the respiratory tract., The frequency and severity of this cough can be used to determine the level of severity of the respiratory infection, Zhijing Wang et al. researched to determine the severity of the cough using a Core symptom score, his research divided the severity of the cough based on the results he obtained, he developed a simplified scoring model called the Simplified cough score that divides cough into 4 crips sets,

I. No cough - when there is no cough.
II. Mild cough - characterized by a transient cough before sleep or occasional cough during the day
III. Moderate Cough - cough mildly affecting night sleep and daily activities.
IV. Frequent or Severe - this usually has a severe effect on sleep and ideally affects the day-to-day activity of the patient.

Given these crisp linguistic variables, we will make a fuzzy set by assigning membership functions for the given 3 distinguishable sets.

Input - Cough (Range 0 - 10)

Linguistic Variable	Mild	Moderate	Severe
Range	0 - 4	2 - 8	6 - 10

Table 1 shows the range of Linguistic variables and membership distribution for cough

Shortness of breath: a pathological condition known as Dyspnoea this is characterized by difficulty in breathing or not having enough air in your lungs, according to the NHS 2019, some of the common causes of shortness of breath include asthma, being overweight, smoking, or even a panic attack, In acute conditions, it can also be a sign of ailments like (COPD) chronic obstructive pulmonary disease lung cancer, all these are signs of respiratory infections.

In 2010 Crisafulli conducted research measuring the level of Dyspnoea he assigned some levels and modified the Borg Scale which is a scale that measures shortness of breath with induced physical exercises he made a range from 0 - 10 and used linguistic variables like None, Mild, Moderate, Intense and Unbearable.

Given these linguistic variables, we will be making a fuzzy set out of this by assigning membership functions to them.

Input – Shortness of breath 0 - 10

Linguistic Variable	Mild	Moderate	High
Range	0 - 4	2 - 8	6 - 10

Table 2 shows the range of Linguistic variables and membership distribution for shortness of breath

Temperature: Fever is a common symptom in humans and it happens due to an increase in body temperature, it is a sign of infections or happens as a result of inflammation (Ozdemır B., Yalçın SS., 2021), Ozdemir researched to determine the effect of temperature on acute respiratory diseases in children showed that in cases like pneumonia, for every 1ºC rise in temperature, there is a significant increase in respiratory rate, According the NHS for respiratory infections like COVID-19 Fever is also a very important symptom to watch out for during the diagnosis.

The normal body temperature of humans ranges from 35ºC to 42ºC according to the NHS (2022) temperature around 38 is considered a high temperature. The linguistic variables for temperature are divided into 4, normal around 36 – around 37.5, elevated around 37 – before 39 while high within 38 – 40, is a high fever above 40 (rossmax.com, n.d. & Mayo Clinic, 2022).

Determining membership functions for fuzzy Input – Temperature 35ºC - 42ºC

Linguistic Variable	Normal	Elevated	High	High Fever
Range	34 - 38	37 - 39.5	38 - 40.5	39.5 - 42

Table 3 shows the range of Linguistic variables and membership distribution for temperature

FUZZY OUTPUT

We are trying to determine the level of respiratory infection based on the input variables and rules, the process of converting fuzzy output to crisp sets is called defuzzification, there are different types of defuzzification we will be testing with 5 of them.

Respiratory Infection: According to the National Institute for Health Care Excellence (2024)., Respiratory infection can be divided into 3 categories: no or low infection, a mild infection characterized by a 1% mortal rate, and a Morbid level by a 10 % mortality risk and morphological changes in the respiratory tract.

Determining membership functions for fuzzy Output – 0 - 1

Linguistic Variable	Low	Medium	high
Range	0 - 0.4	0.2 - 0.8	0.6 - 1

Table 4 shows the range of Linguistic variables and membership distribution for respiratory infection

RULES

I have selected a total of 15 rules for this system these rules were selected based on a combination of severity of the variables.

a. Temperature – Normal, Elevated, High, Very High.
b. Shortness of Breath – Low, Moderate, High.
c. Cough – Mild, Moderate, Severe.
d. Respiratory Infection – Low, Medium, High.

From the symptoms varying levels of infections are implications of different combinations of these input variables, these subset of rules are gathered from the expert domain from determining the score of Infections, based on physical diagnosis.

The total number of rules from the system leads to a total of 36 possible rules. These rules were reduced to 15 because most rules are redundant, overlapped, or have a more dominant combination.

The rules show the possible outcome when the infection is low, and the combination when the infection is high or medium, as obtained from the symptoms scoring pattern for the output variables we used the and connection for all the rules below.

1. If Temperature is elevated Shortness of breath is low, and Cough is mild then Infection is low.
2. If Temperature is normal and Shortness of breath is moderate, and Cough is mild then Infection is medium.
3. If Temperature is high Shortness of breath is moderate, and the Cough is mild then the Infection is medium.
4. If Temperature is elevated and Shortness of breath is high, and Cough is mild then Infection is medium.
5. If Temperature is high and Shortness of breath is low, and Cough is moderate then Infection is medium.
6. If the Temperature is elevated Shortness of breath is moderate, and Cough is moderate then Infection is medium.
7. If Temperature is high and Shortness of breath is moderate, and Cough is moderate then Infection is high.
8. If Temperature is elevated and Shortness of breath is high, and Cough is moderate then Infection is high.
9. If Temperature is high and Shortness of breath is high, and Cough is moderate then Infection is medium.

10. If Temperature is high and Shortness of breath is low, and Cough is severe then Infection is medium.
11. If Temperature is elevated Shortness of breath is moderate, and Cough is severe then Infection is high.
12. If Temperature is high and Shortness of breath is moderate, and the Cough is severe then the Infection is high.
13. If Temperature is high and Shortness of breath is high, and Cough is severe then Infection is high.
14. If Temperature is very high and Shortness of breath is high, and Cough is severe then Infection is high.
15. If Temperature is high and Shortness of breath is low, and Cough is mild then Infection is low.

TUNING MEMBERSHIP FUNCTIONS

Choosing the appropriate membership function.

There is no specific way to represent the membership function for a set, as there are quite several ways to graphically show this, instead, it is more important to choose the correct range for the membership rather than the shape (Sadollah 2018). For example, the fuzzy set for the linguistic variables around 10, before 5 around 7, and 8. It is important to know where these MF will be placed rather than the shape however the MF must be between 1 and 0.

Some sources state that it is advisable to use a triangular MF because they are easy to implement and represent a single number, trapezoidal when we want to express intervals of numbers, other shapes can be implemented by the transformation of the triangular MF (Sadollah 2018). Some studies also show that a combination of two types gives the most accurate and straightforward answers while too many membership functions showed a reduction in performance (Sadollah 2018).

Different combinations of membership functions give slightly different results since this is a medical problem given its stringent nature of medical problems, care must be taken to achieve the most efficient and correct solution. I will be using a combination of some membership function curves and will discuss the best combination based on the smoothest surface plot, the most accurate result, and sensitivity analysis.

I will be doing some tuning between MFs to obtain the most efficient option or combination, I will be using a total of 5 combinations, as these are the most common combination for fuzzy logic systems.

i. Gaussian (GUA)
ii. Triangular (TRI)
iii. Triangular and Trapezoidal (TRI_TRAP)
iv. Sigmoid and Gaussian (SIG_GAU)
v. Trapezoidal (TRAP)

From the surface plots shown in **Appendix 1** it is evident that the GUA surface plot gave the smoothest surface, this means we have smoother transitions and a very sensitive system we will also go ahead to test the performance of each of these combinations of the membership functions to determine the error rate and proceed with elements with most minimal error, a mixture of triangular and trapezoidal MF also showed a great gentle slope with promising efficiency, we will move on to test these membership functions to prove their efficiency in diagnosis this ailment.

TEST CASES

Clinical Case 1

A 33-year-old white female presents complained of shortness of breath on exertion. Her history showed she had had bronchitis and was treated 6 months earlier but her symptoms continued, upon physical examination, she had a 36.5°C temperature, had mild wheezing, and was able to communicate but stopped mid-sentence because of difficulty in breathing, she also had a cough (Sharma S. et al, 2020).

Initial Diagnosis: Mild interstitial pneumonitis

Confirmed Diagnosis: Acute pulmonary histoplasmosis (Sharma S. et al, 2020)

FIS Input: Temperature - 36.5, Shortness of breath - 7, Cough 7

Expected FIS output: Medium-high probability of respiratory infection

Clinical Case 2

A 35-year-old male resident of Boston, Massachusetts, had a cough that had persisted over 14 days he decided to seek a physician as his temperature had increased to 38.3°C and coughs followed by secretions, upon examination his temperature was 38.9°C, low oxygen saturation of 93% show a mild difficulty in breathing including the respiratory rate (David N. 2008).

Initial Diagnosis: Mild pneumonia

Confirmed Diagnosis: pneumococcal pneumonia superimposed on a viral upper respiratory tract infection (David N. 2008).

FIS Input: Temperature - 38.9, Shortness of breath - 6, Cough 8

Expected FIS output: Medium to high probability of respiratory infection

Clinical Case 3

A 40-year-old man without previous medical background landed in an emergency, he complained of a one-week cough high fever and chest pain. His condition deteriorated and he was put in the ICU due to respiratory failure and he ran into septic shock and renal failure (Talavera, M. et al., 2023).

Initial Diagnosis: Acute Respiratory Infection

Confirmed Diagnosis: He tested positive for Metapneumovirus (Talavera, M. et al., 2023)

FIS Input: Temperature - 40.5, Shortness of breath - 9, Cough 7.5

Expected FIS output: High probability of respiratory infection

Clinical case 4

An 11-year-old boy from northern Thailand had a fever for 10 days, he showed no symptoms of chills, and no cough, but a slightly increased respiratory rate, on examination he had an enlarged tonsils, breath seemed normal but an increase in heart rate, he looked pale.

Initial Diagnosis: Infection but not respiratory-related.

Final Diagnosis: He tested positive for malaria. (S.A. Issaranggoon et al. 2014).

FIS Input: Temperature - 39.7, Shortness of breath - 2, Cough 1

Expected FIS output: Low probability of respiratory infection.

RESULTS

From the clinical cases we have above, we compared the result of each combination of the membership function and the output of the combination, we have an expected result for each of the clinical cases, if the output is not close to the expected range then there is a high error., Appendix 3 contains the membership function plot for the 5 sets of the membership function while Appendix 2 shows the rule inference, we used the same value for all the membership functions and recorded the values based on the 5 defuzzification technique, the results for the 4 cases are shown in Appendix 4.

Deffuxification Technique:

I. Centriod (Centroid of Area)
II. Bisector (Bisector of Area Method)
III. LOM (Last of Maxima Method)
IV. MOM (Mean of Maxima Method)
V. SOM (Smallest of Maximum)

Given that the expected result for clinical cases should be

I. Case 1: Medium – high probability of respiratory infection (0.5 – 0.7).
II. Case 2: Medium-high probability of respiratory infection around 0.6 - around 0.8
III. Case 3: High probability of respiratory infection approximate expected value from the result should give a range of around 0.8 to around 0.9.
IV. Case 4: Low probability of respiratory infection Around 0.1 – 0.2.

The results for the FIS in test case one showed good results for all the different defuzzification techniques except for 'LOM' and SOM techniques they gave off values as seen in table 5 in appendix 4.

The results for case 2 showed great results LOM had a terrible result while SOM seemed to have performed better, MOM for all MFs gave values that were overly beyond the expected outcome for all membership functions, it can also be noticed that the trapezoidal membership function showed very terrible fit for this problem.

The results from Table 7 show values within the range of expected outcomes, the MOM defuzzification technique seems to be the best-performing method here as it handled the most projection towards the extreme, relatively other values were within the range of the expected outcome except the SOM technique.

Test case 4 was diagnosed to be malaria rather than respiratory diseases, the FIS system did well to capture the result in that manner, it was evident that every membership function combination had predicted correctly the outcome to be significantly very low which inclined with the expected outcome.

These results show that in all clinical cases, the centroid and bisector defuzzification techniques yielded the best results that were close to the expected outcome while LOM and SOM performed poorly, the gaussian provided the best result we could see a clear disparity in the output as the severity of the case increases, this is most likely because of the smooth surface plot of the chart as seen in figure 3. The trapezoidal however performed the list because of the presence of rough edges and could not give a good accurate disparity between the edges.

CONCLUSION AND RECOMMENDATION

The importance of fuzzy logic in health care cannot be emphasized, the process of using fuzzy systems to convert crisp sets to fuzzy sets helps provide a framework where traditional logic fails because of uncertainty and lack of precision. With the presence of membership functions, we can then use fuzzy systems on data that is not certain or precise like saying the cough is 8 in test case 2, fuzzy systems have effectively been able to handle Ambiguity in solving this problem, rules also help ensure that professional in this domain can express their knowledge on the system., however, some of the limitations of fuzzy systems include difficulty in tuning to get the perfect plot, handling edge cases, no appropriate or universal standards as no one standard says infections should be weighed in this scale, and so there are a lot of difficulties in comparing, the computational efficiency of the fuzzy system.

From this research I was able to implement the Mamdani type 1 fuzzy system and was able to determine Respiratory infections in humans by investigating 3 variables, I obtained datasets by using secondary resources and carried out a performance comparison of MFs to determine the most efficient combination of MF, It was clear that all compared membership functions performed properly except the trapezoidal MF. The Gaussian MF was the best.

Further work can be done to find out the most optimal parameters using Optimization functions like the Particle Swarm Optimization technique or Genetic Algorithm to find the minimum error gradient between the output and the desired output.

While we developed a performant Fuzzy system to determine the level of probability of Respiratory Infection, this should not be taken as the final diagnosis but as an initial diagnosis for respiratory infection, more tests should be carried out to determine the type of infection and the causative agent by microscopic examination of sputum xrays, etc.

Appendix 1 – Comparison of Surface Plots

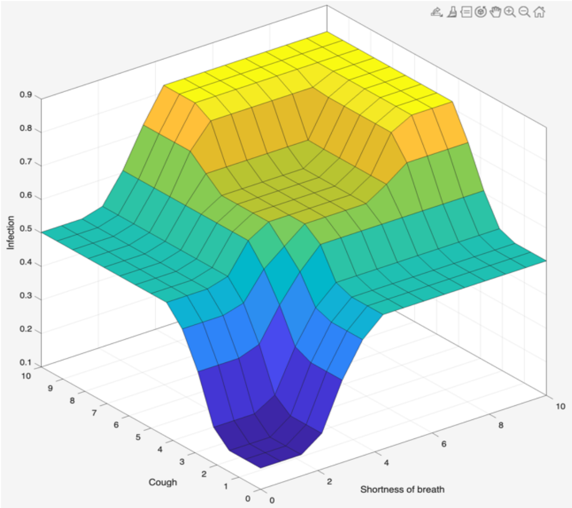


Figure 1surface plot showing trapezoidal and triangular MFs

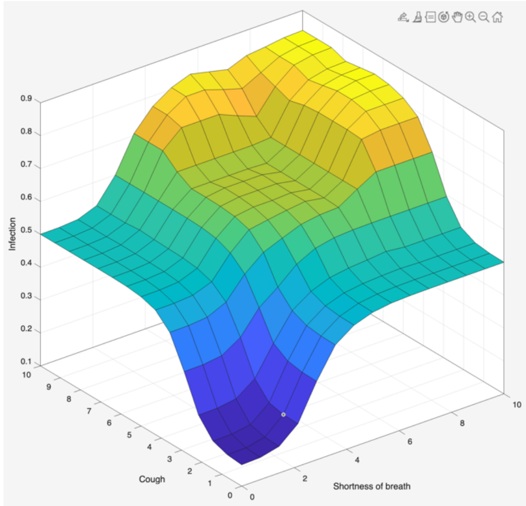


Figure 3 shows a surface plot of just Gaussian MFs

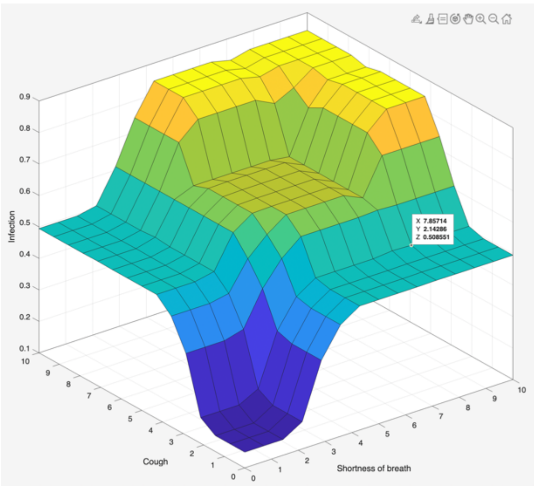


Figure 2 shows a surface plot of just trapezoidal MFs

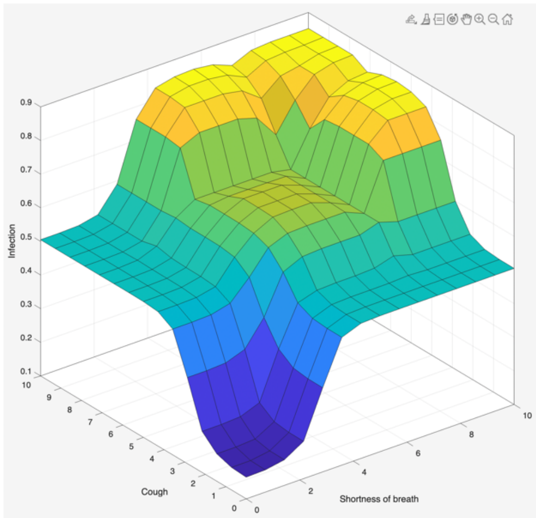


Figure 4 shows the surface plot for sigmoid and guassianMFs

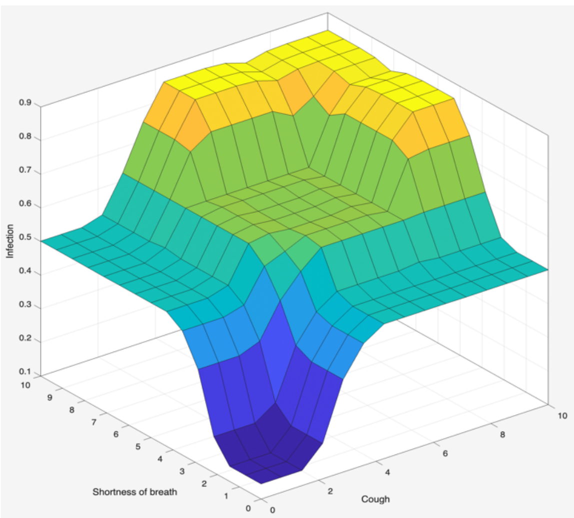


Figure 5 shows a surface plot of just triangular MFs

Appendix 2 – MF Figures

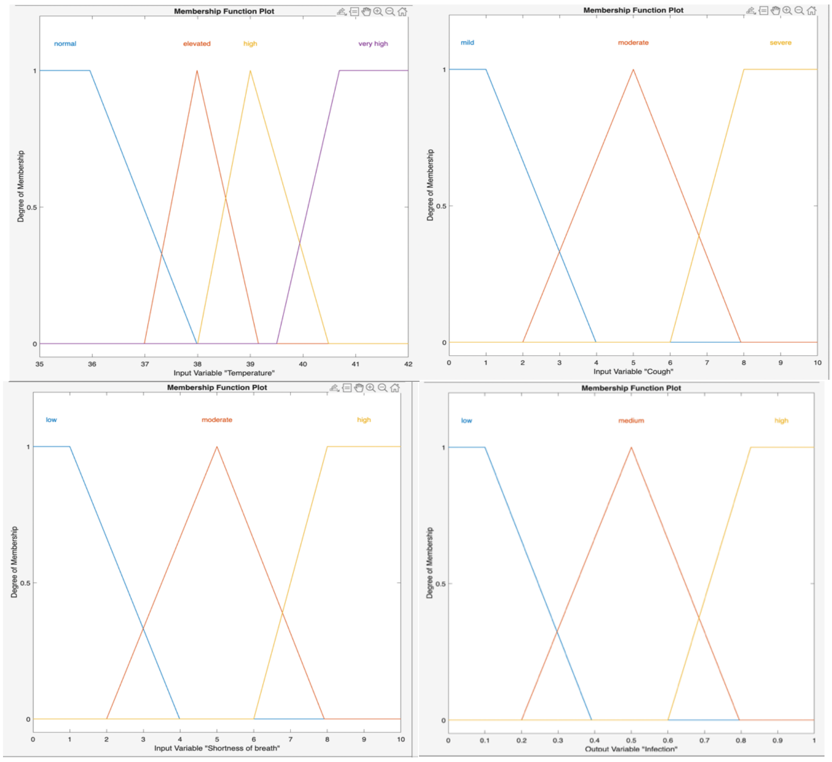


Figure 6 showing MF plot with traingular and Trapeziodal MF for all parameters

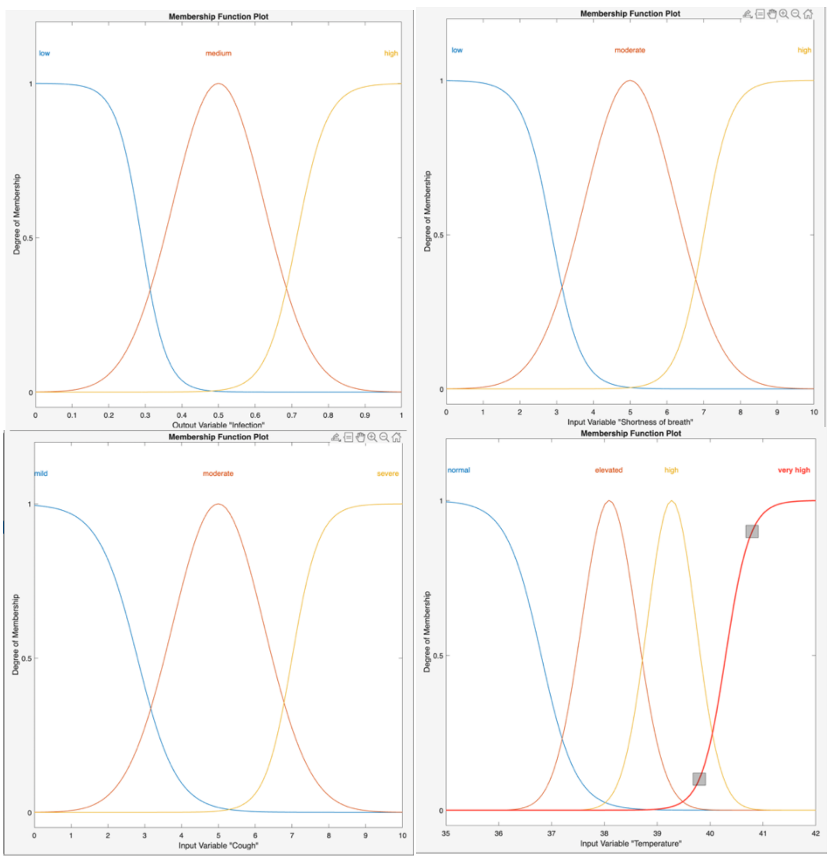


Figure 7 shows the MF plot combining sigmoid and guassian MF on all parameters

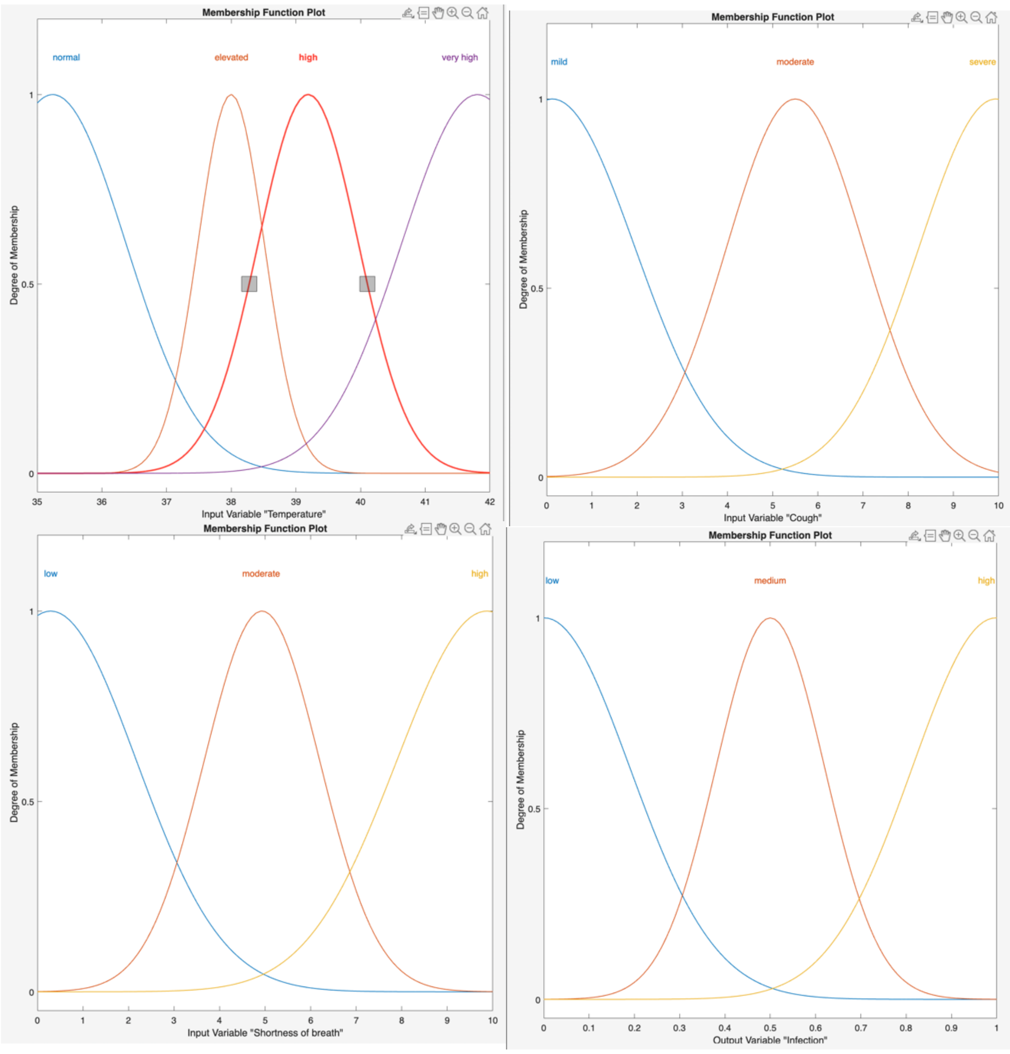


Figure 8 Sigmoid MF plot for all linguistic variables

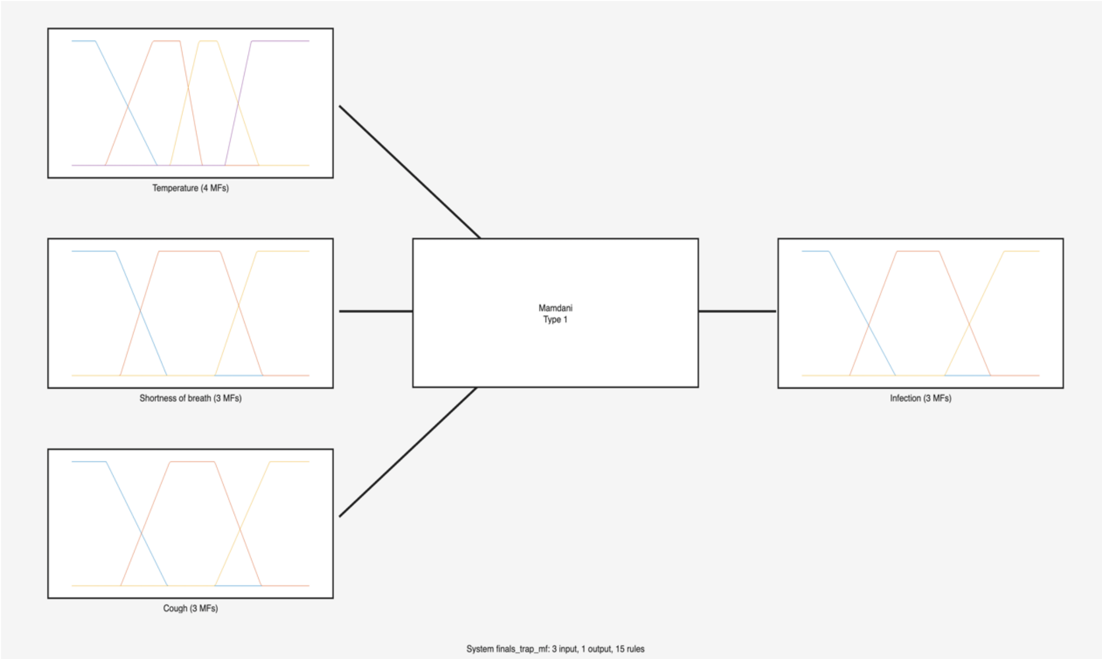


Figure 10 FIS high level overview showing trapezoidal MFs for all linguistic variables

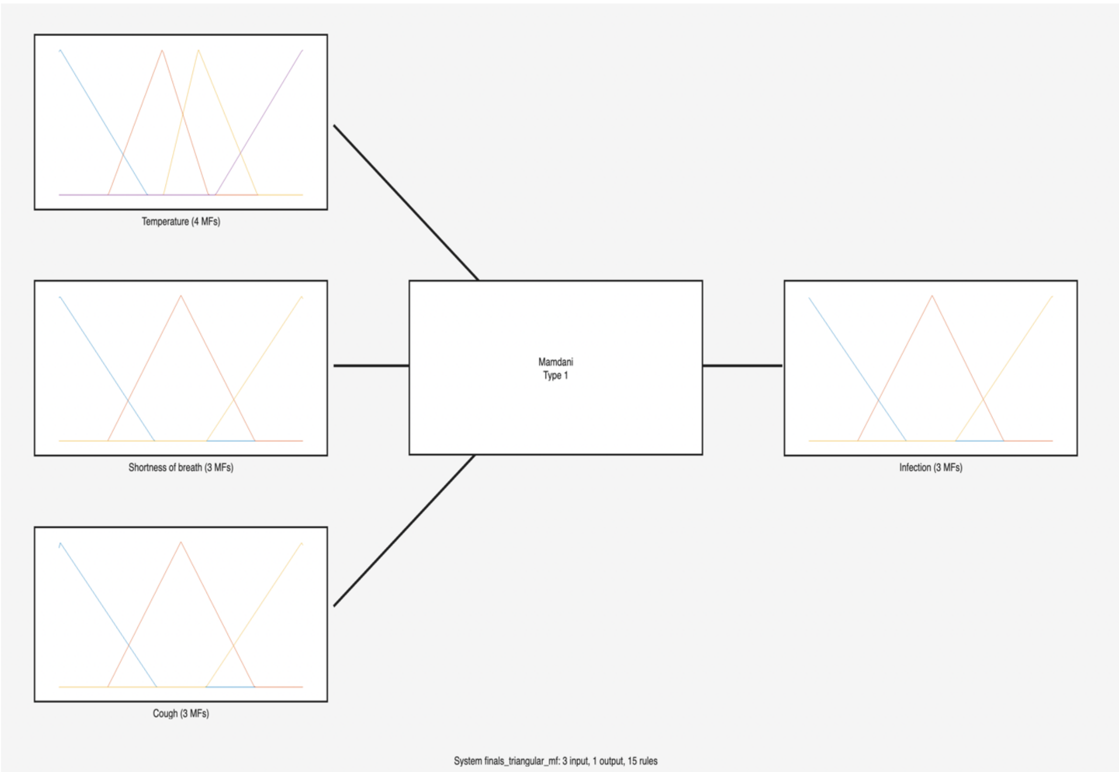


Figure 9 FIS high level overview showing triangular MFs for all linguistic variables

Figures showing the Rule Inference of Triangular and Trapezoidal membership functions.

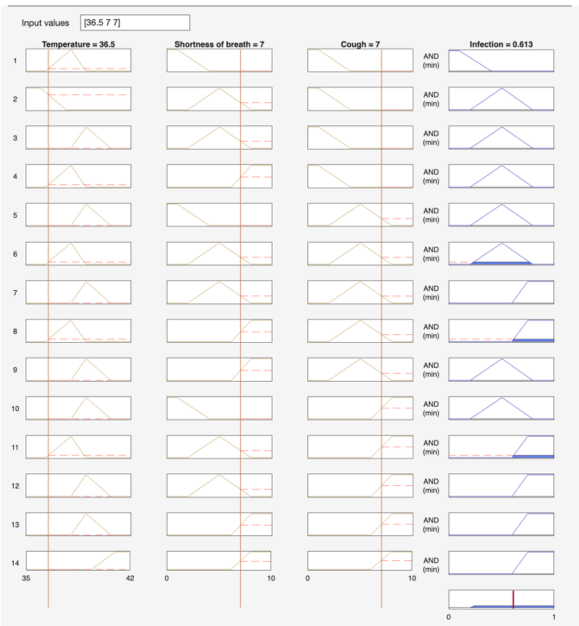


Figure 11 Effect of Triangular and Trapezoidal MFs Inference System on Clinical Test Case 1

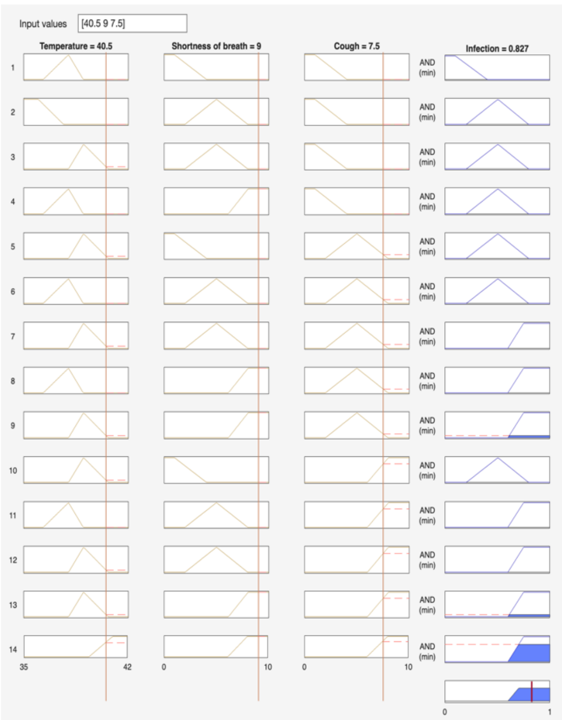
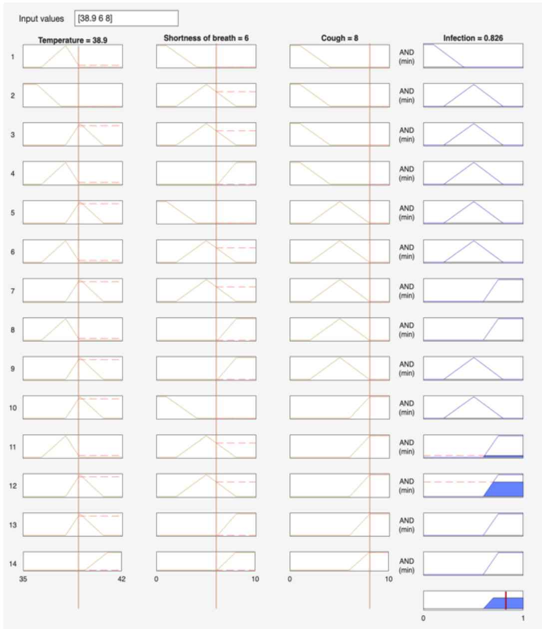


Figure 13 Effect of triangular and Trapezoidal MFs Inference system on Clinical Test Case 3

Figure 12 Triangular and Trapezoidal Rule Inference on Clinical Test Case II



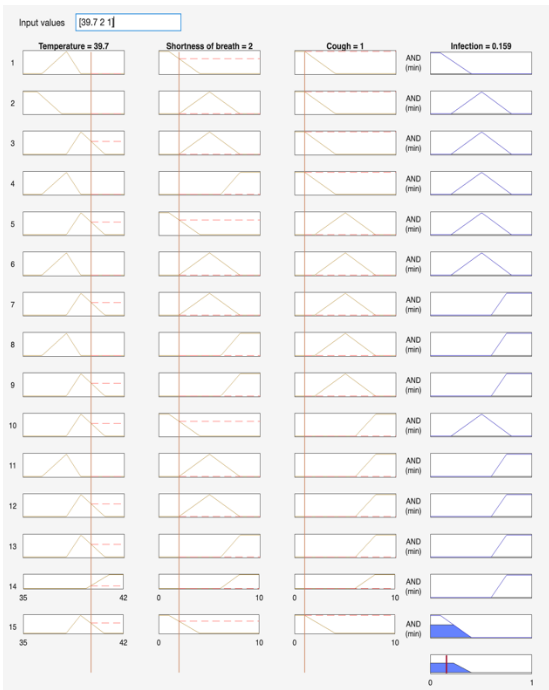


Figure 14 Effect of triangular and Trapezoidal MFs Inference system on Clinical Test Case 4

Figures showing the Rule Inference of Triangular membership functions.

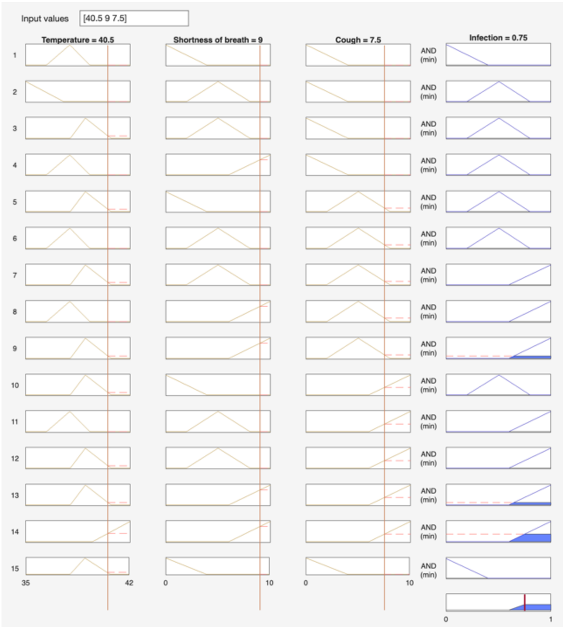


Figure 16 Effect of triangular MF Inference system on Clinical Test Case 3

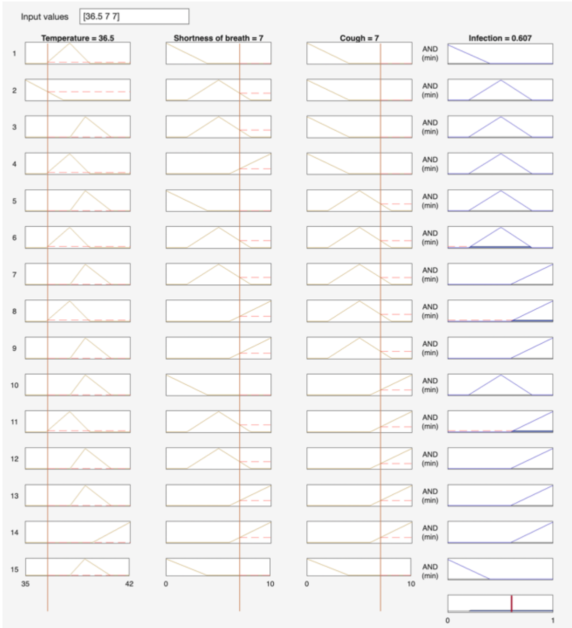


Figure 15 Effect of triangular MFs Inference system on Clinical Test Case 1

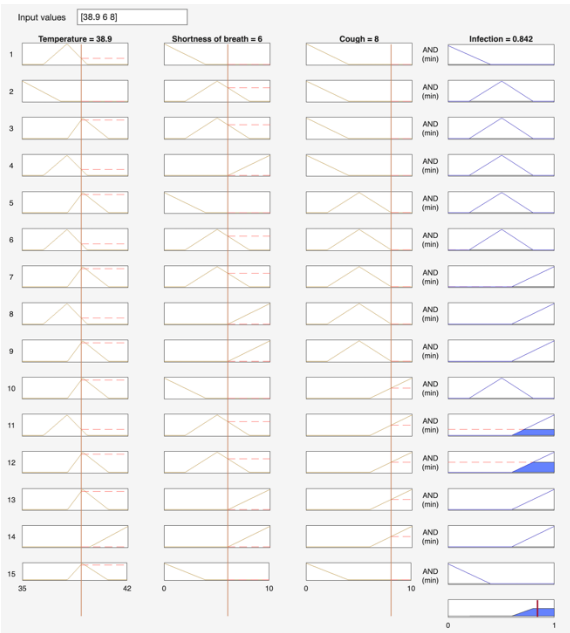


Figure 18 Effect of triangular MFs Inference system on Clinical Test Case 4

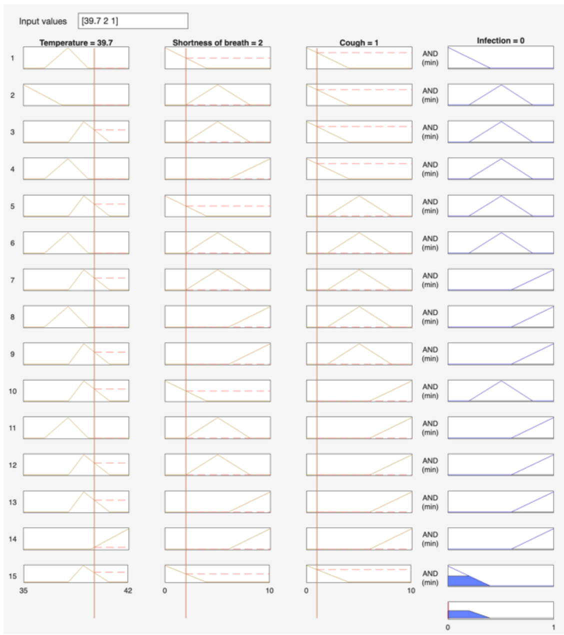


Figure 17 Effect of triangular MFs Inference system on Clinical Test Case 4

Figures showing the Rule Inference of Sigmoid and Gaussian membership functions.

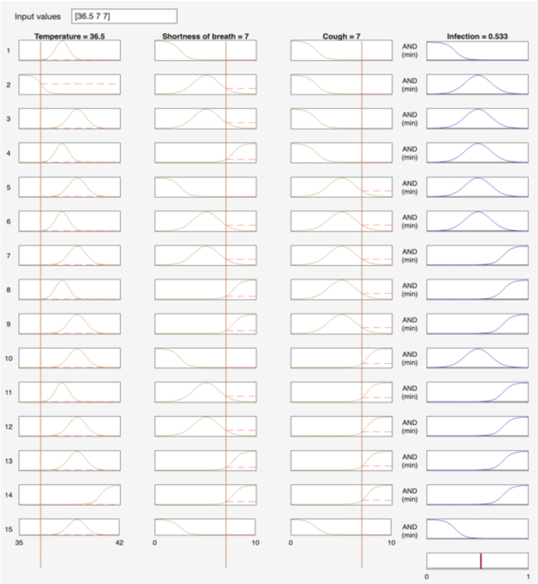


Figure 19 Effect of Guassian MFs Inference system on Clinical Test Case 4

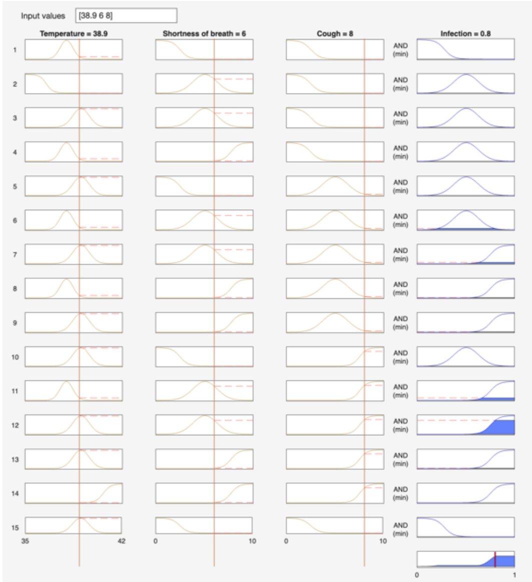


Figure 20 Effect of Gaussian MFs Inference system on Clinical Test Case 2

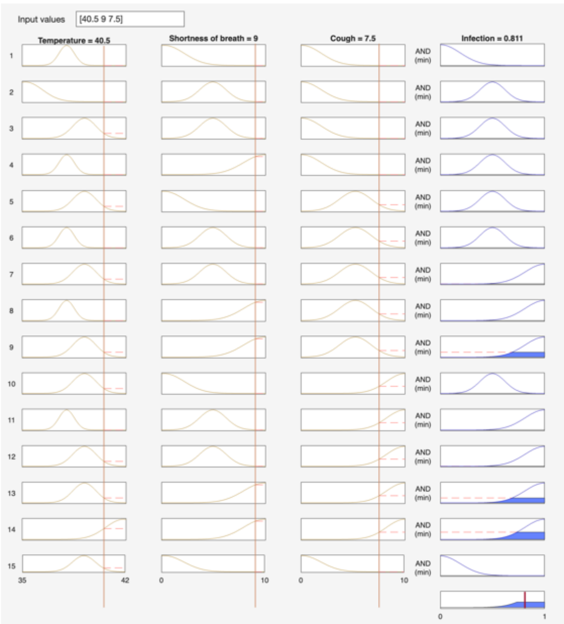


Figure 21 Effect of Gaussian MFs Inference system on Clinical Test Case 3

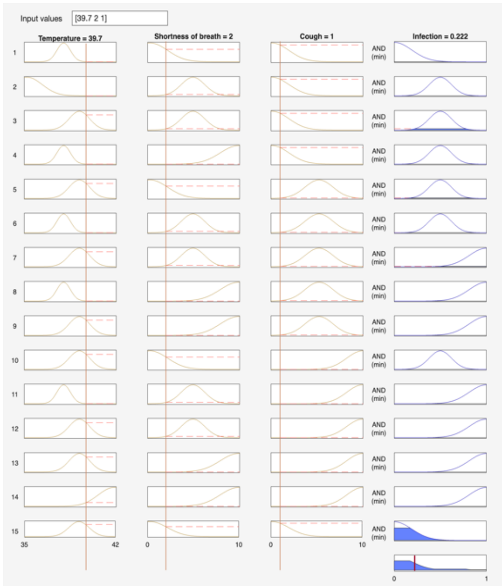


Figure 22 Effect of Gaussian MFs Inference system on Clinical Test Case 1

Figures showing the Rule Inference of Triangular membership functions.

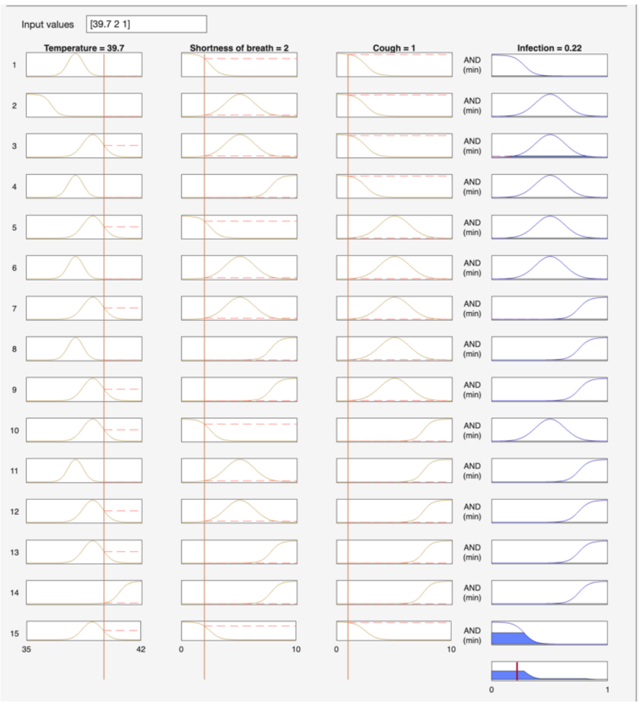


Figure 24 Effect of Sigmoid & Gaussian MFs Inference system on Clinical Test Case 4

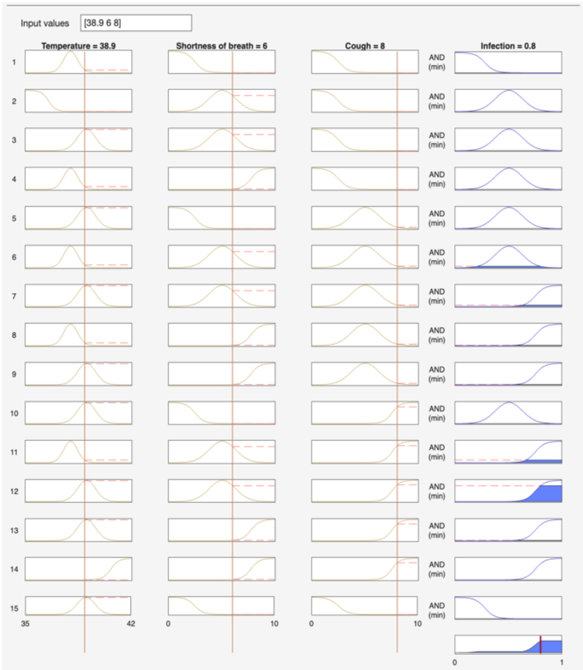


Figure 23 Effect of sigmoid & Gaussian MFs Inference system on Clinical Test Case 2

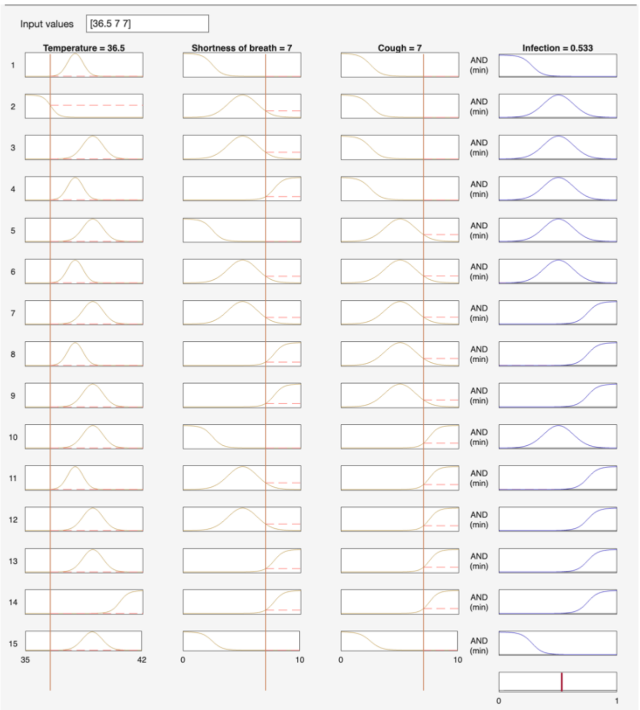


Figure 26 Effect of sigmoid and Gaussian MFs Inference system on Clinical Test Case 1

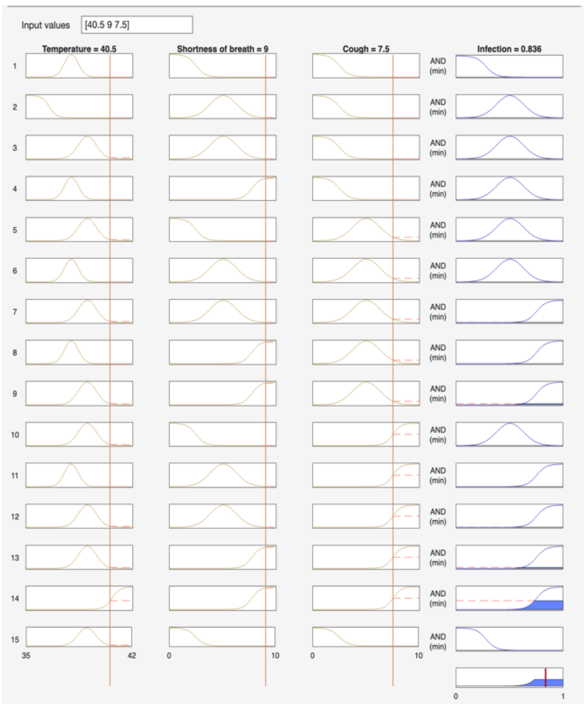


Figure 25 Effect of sigmoid and Gaussian MFs Inference system on Clinical Test Case 1

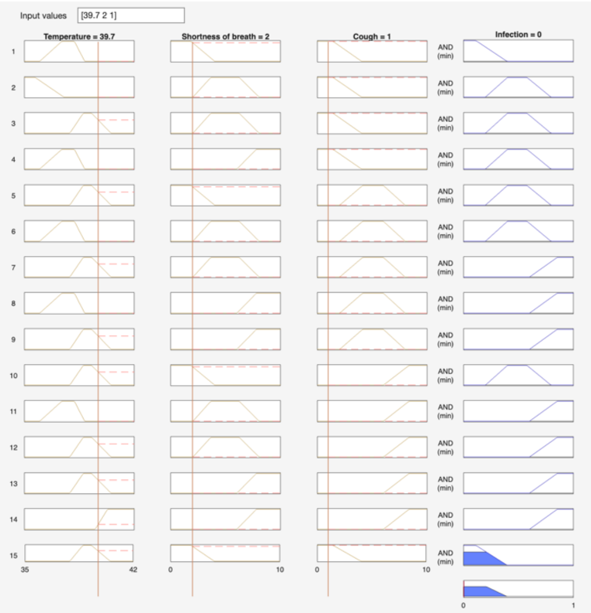
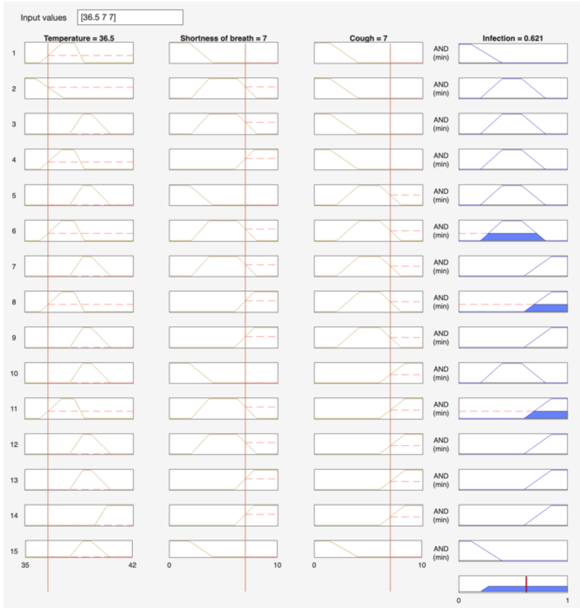


Figure 28 Effect of trapezoidal MF Inference system on Clinical Test Case 4

Figure 27 Effect of triangular MF Inference system on Clinical Test Case 1



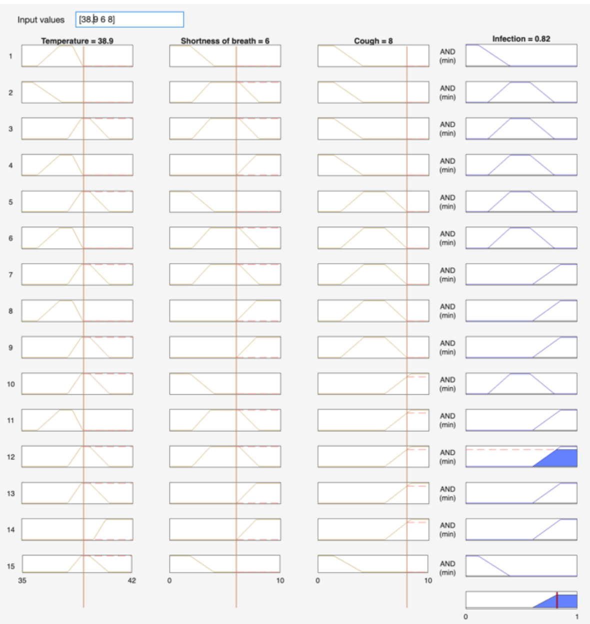


Figure 30 Effect of Trapezoidal MF Inference system on Clinical Test Case 2

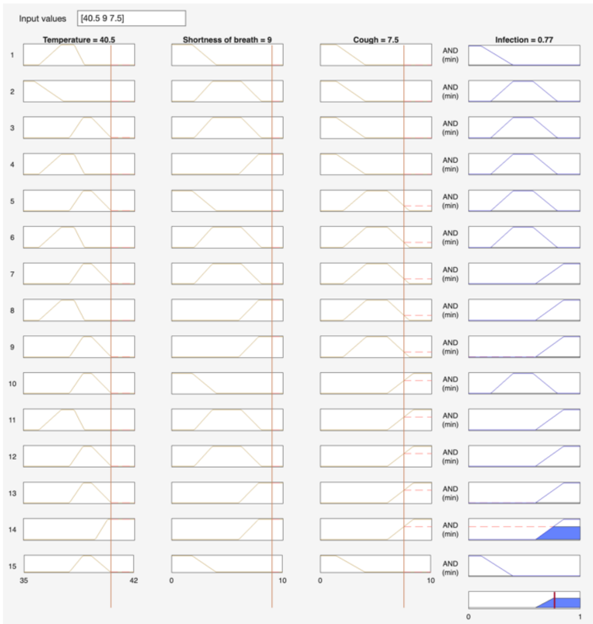


Figure 29 Effect of trapezoidal MF Inference system on Clinical Test Case 3

Appendix 4 Tables showing results

TEST CASE 1	Defuzzification Methods				
MF	Centroid	BISECTOR	LOM	MOM	SOM
GUA	0.557	0.56	1	0.575	0.15
TRI	0.607	0.61	1	0.61	0.22
TRI_TRAP	0.613	0.61	1	0.62	0.24
SIG_GAU	0.533	0.53	1	0.55	0.1
TRAP	0.621	0.62	1	0.64	0.28

Table 5 shows the result of all membership functions for Test Case I

TEST CASE 2	Defuzzification Methods				
MF	Centroid	BISECTOR	LOM	MOM	SOM
GUA	0.71	0.78	1	0.895	0.79
TRI	0.842	0.84	1	0.9	0.8
TRI_TRAP	0.76	0.79	1	0.84	0.68
SIG_GAU	0.8	0.84	1	0.905	0.81
TRAP	0.85	0.86	1	0.91	0.82

Table 6 shows the result of all membership functions for Test Case II

TEST CASE 3	Defuzzification Methods				
MF	Centroid	BISECTOR	LOM	MOM	SOM
GUA	0.811	0.82	1	0.87	0.74
TRI	0.837	0.84	1	0.875	0.75
TRI_TRAP	0.827	0.83	1	0.855	0.71
SIG_GAU	0.836	0.84	1	0.87	0.74
TRAP	0.839	0.84	1	0.885	0.77

Table 7 shows the result of all membership functions for Test Case III

TEST CASE 4	Defuzzification Methods				
MF	Centroid	BISECTOR	LOM	MOM	SOM
GUA	0.222	0.17	0.17	0.085	0
TRI	0.153	0.15	0.2	0.1	0
TRI_TRAP	0.159	0.16	0.22	0.11	0
SIG_GAU	0.22	0.19	0.27	0.135	0
TRAP	0.153	0.15	0.2	0.1	0

Table 8 shows the result of all membership functions for Test Case IV

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