

CHAPTER-6

FUZZY BASED BRIDGE RATING SYSTEM (FBRS) FOR CONDITION ASSESSMENT OF EXISTING RAILWAY BRIDGES

6.1 General

Railway bridges play a critical role in the transportation infrastructure of any country. The safe and efficient operation of railway bridges is essential for the movement of people and goods across the country. However, these structures are subject to various environmental and operational factors that can lead to degradation over time. The maintenance and management of these structures are essential to ensure their safe operation and longevity. Condition rating is a crucial aspect of maintaining and managing railway bridges. It is the process of evaluating the physical condition of the bridge components, identifying any defects or damage, and determining the severity of the damage. The condition rating system is essential for prioritizing maintenance and repair activities, budgeting, and developing long-term maintenance plans.

Under a programme IBMS, MoRTH, India recently inventoried (MoRTH 2019) 172,517 bridges that are located along national highways in India. This information includes 1,34,229 culverts (up to 6 m in span), 32,806 minor bridges (6 to 60 m in span), 3,647 major bridges (60 to 150 m in span), and 1835 extra-long bridges (more than 150 m in span). Garg et al. (2020) presented analysis of Indian highway bridge failures during 1977 to 2017 in which they have taken more than 2000 existing bridges. In Indian railways, there are three different types of bridges: minor, major, and crucial. According to (India Yearbook 2021–2022), Indian Railways has 1.56 lakh bridges as of April 2022, of which 143088, 12590, and 739 were minor, major,

and important bridges, respectively. Less than 0.5% of all bridges in the Indian Railways are considered important. The Indian Railways system had 1.40 lakh bridges as of April 2016, of which 27% were older than 100 years and 34% were older than 80 years (Awasthi et al. 2022). For railway bridges, minor, major, and important bridge are defined by bridge sub-structures & foundation code (RDSO 2013). Over one-third of the Indian Railways' current bridges are older than 80 years.

6.2 Railway bridge components

Different components of a railway bridge include foundation, substructure, training and protection (T & P) works, bed blocks, bearing, superstructure, and railway track. These components are illustrated in Figure 6.1.

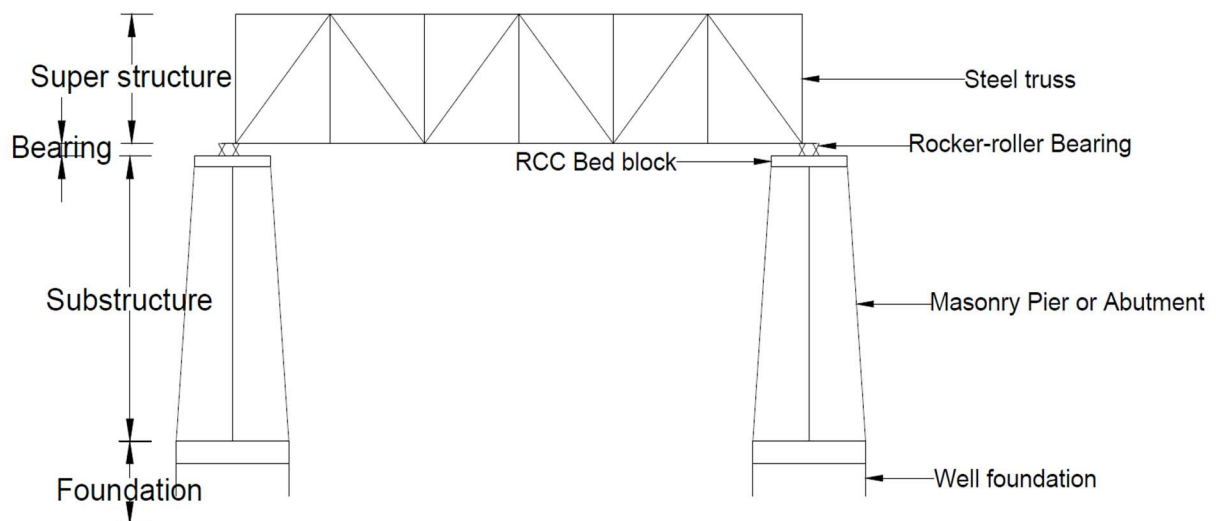


Figure 6.1: Different components of a railway bridge

6.3 Fuzzy logic and fuzzy weighted geometric mean (FWGM)

Each crisp rating r assigned to an element or symptom is associated with the fuzzy set R defined as follows:

$$R = \{\max(r - 1, 1), \quad r, \quad \min(r + 1, 10)\} \quad (6.1)$$

Mathematically, for a given fuzzy set A defined on the universe of discourse X , an α -cut at a specific threshold α is denoted as A_α and defined as follows:

$$A_\alpha = \{x \in X \mid \mu_{\tilde{A}}(x) \geq \alpha\} = [\min\{x \in X \mid \mu_{\tilde{A}}(x) \geq \alpha\}, \max\{x \in X \mid \mu_{\tilde{A}}(x) \geq \alpha\}] \quad (6.2)$$

where $\mu_A(x)$ represents the membership degree of element x in the fuzzy set A . In simple terms, the α -cut A_α includes all elements from the universe of discourse X for which the membership degree in the fuzzy set A is greater than or equal to α .

Figure 6.2 illustrates trapezoidal membership function (MF). Triangular MF is special case of trapezoidal MF with $q=r$ (if x axis values are $p, q, r,$ and s) or $(x)_{\alpha_n}^L = (x)_{\alpha_n}^U$ (if x axis values are $(x)_{\alpha_0}^L, (x)_{\alpha_n}^L, (x)_{\alpha_n}^U,$ and $(x)_{\alpha_0}^U$).

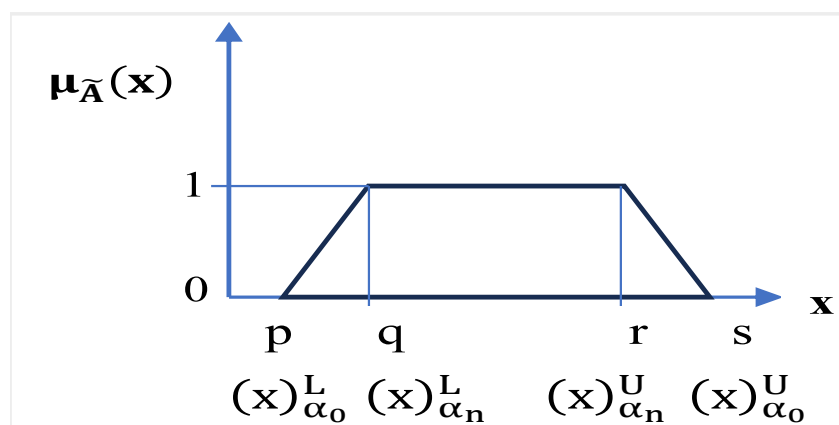


Figure 6.2: Trapezoidal membership function

Defuzzification: The centroid method defines a centroid of fuzzy number \tilde{A} as its defuzzified value, and is defined as follows (Yager 1981):

$$\bar{x}_0(\tilde{A}) = \frac{\int_p^s x \mu_{\tilde{A}}(x) dx}{\int_p^s \mu_{\tilde{A}}(x) dx} \quad (6.3)$$

Where $\bar{x}_0(\tilde{A})$ is a defuzzified value. To defuzzify a triangular fuzzy number $\tilde{A} = (p, q, s)$ centroid expression is used as follows:

$$\bar{x}_0(\tilde{A}) = \frac{p + q + s}{3} \quad (6.4)$$

When fuzzy number (\tilde{A}) is presented by α -cuts, i.e.,

$$(\tilde{A}) = \cup_{\alpha} \alpha \cdot A_{\alpha} = \cup_{\alpha} \alpha \cdot [(x)_{\alpha}^L, (x)_{\alpha}^U] \quad (0 < \alpha \leq 1),$$

Its defuzzified centroid form can be expressed as follows (Wang et al. 2009):

$$\bar{x}_0(\tilde{A}) = \frac{\int_p^s x \mu_{\tilde{A}}(x) dx}{\int_p^s \mu_{\tilde{A}}(x) dx} = \frac{(x)_{\alpha_0}^U + (x)_{\alpha_n}^L + (x)_{\alpha_0}^L}{3} = \frac{(x)_{\alpha_0}^U + (x)_{\alpha_n}^U + (x)_{\alpha_0}^L}{3} \quad (6.5)$$

Expression (5) represents the defuzzification by the centroid method for a triangular fuzzy number.

The average value of n fuzzy numbers has been obtained using FWGM approach expressed as follows:

$$\tilde{y}_G = \prod_{i=1}^n (\tilde{x}_i)^{\frac{\tilde{w}_i}{\sum_{i=1}^n \tilde{w}_i}} \quad (6.6)$$

where $\tilde{x}_1, \tilde{x}_2, \dots, \tilde{x}_n$ are n fuzzy numbers, and $\tilde{w}_1, \tilde{w}_2, \dots, \tilde{w}_n$ are corresponding fuzzy weights. It is clear that \tilde{y}_G , is also fuzzy number which can be calculated using α -cuts and Zadeh's principle of fuzzy number addition (Zadeh 1965).

6.4 Methodology

6.4.1 Basic methodology

In bridge condition evaluation, fuzzy logic, a theory commonly used in construction engineering, is used. A modified version of fuzzy logic is used in this methodology to add structural significance analysis of bridge parts. The VI-based method for assessing the state of existing bridges uses either conventional fuzzy logic or the FWA technique. The application of fuzzy weighted geometric mean (FWGM) for railway bridge assessment is presented in this study.

This section presents the study methodology, which concentrates around the use of fuzzy logic and defuzzification techniques. Fuzzy logic is used to deal with uncertainty and imprecise data, whereas defuzzification converts fuzzy output into crisp values for further analysis and decision-making. This methodology gives a solid framework for dealing with difficult situations and gaining significant insights from fuzzy data.

Steps of bridge rating are as follows:

1. Assign a crisp rating to elements from 1 to 10. The component condition rating is determined by a structural expert. To ensure accuracy and objectivity in assessing the

bridge condition, the proposal suggests dividing it into 10 fuzzy sets. Based on the assigned rating, the corresponding fuzzy set(s) are identified in which the rating falls. Assuming the crisp value of rating x be a part of set $S = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$, then

$$\text{for each } x \in S : (R_{E_i})_k = ((\tilde{R}_{E_i}^L)_k, (\tilde{R}_{E_i}^M)_k, (\tilde{R}_{E_i}^U)_k), k = 1, 2 \text{ \& } 3; i = 1, 2, \dots, n \quad (6.7)$$

$$\text{for each } x \notin S : (R_{E_i})_k = ((\tilde{R}_{E_i}^L)_k, (\tilde{R}_{E_i}^M)_k, (\tilde{R}_{E_i}^U)_k), k = 1 \text{ \& } 2; i = 1, 2, \dots, n \quad (6.8)$$

where $(R_{E_i})_k$ is the k^{th} fuzzy rating set of i^{th} element.

2. Calculating the total count of combinations by considering all elements across different rating conditions defined by crisp values:

$$N_{\text{comb}} = \prod_{i=1}^n ((\tilde{R}_{E_i}^k), (\tilde{w}_{E_i})) \quad (6.9)$$

where \tilde{w}_{E_i} is the weight or structural importance of i^{th} element. N_{comb} is number of combinations.

3. Determining α -cuts for fuzzy values of ratings of element by all combinations using linear programming model:

$$\text{Min } z_1 = v_1 \ln(\tilde{R}_{E_1}^L)_\alpha + v_2 \ln(\tilde{R}_{E_2}^L)_\alpha + \dots + v_n \ln(\tilde{R}_{E_n}^L)_\alpha$$

$$v_1 + v_2 + \dots + v_n = 1 \quad (6.10)$$

$$\begin{cases} (w_{E_1}^L)_\alpha \cdot z \leq v_1 \leq (w_{E_1}^U)_\alpha \cdot z, \\ \vdots \\ (w_{E_n}^L)_\alpha \cdot z \leq v_n \leq (w_{E_n}^U)_\alpha \cdot z \end{cases}$$

&

$$\text{Max } z_2 = v_1 \ln(\tilde{R}_{E_1}^U)_\alpha + v_2 \ln(\tilde{R}_{E_2}^U)_\alpha + \dots + v_n \ln(\tilde{R}_{E_n}^U)_\alpha$$

$$v_1 + v_2 + \dots + v_n = 1 \quad (6.11)$$

$$\begin{cases} (w_{E_1}^L)_\alpha \cdot z \leq v_1 \leq (w_{E_1}^U)_\alpha \cdot z, \\ \vdots \\ (w_{E_n}^L)_\alpha \cdot z \leq v_n \leq (w_{E_n}^U)_\alpha \cdot z \end{cases}$$

Where $\ln(x) = \log_e(x)$, $[\ln(\tilde{R}_{E_1}^L)_\alpha, \ln(\tilde{R}_{E_1}^U)_\alpha], \dots, [\ln(\tilde{R}_{E_n}^L)_\alpha, \ln(\tilde{R}_{E_n}^U)_\alpha]$ denotes sets of α -cuts for fuzzy elements rating by all combinations.

$[\ln(\tilde{w}_{E_1}^L)_\alpha, \ln(\tilde{w}_{E_1}^U)_\alpha], \dots, [\ln(\tilde{w}_{E_n}^L)_\alpha, \ln(\tilde{w}_{E_n}^U)_\alpha]$ are sets of α -cuts for fuzzy values of elements weight across all possible combinations.

The linear programming models indicated above are applications of models for the fuzzy grade of component value according to all combinations for all α -cuts.

- Calculating the average value of the element's α -cut value of fuzzy rating over all combinations using the FWGM approach:

$$\tilde{y}_G = \prod_{i=1}^n (\tilde{x}_i)^{\frac{\tilde{w}_i}{\sum_{i=1}^n \tilde{w}_i}} \quad (6.12)$$

- Calculating the average value of the element's fuzzy rating based on the computed α -cuts as:

$$(R_C) = \frac{1}{n} \sum_{i=1}^n [(R_C^L)_\alpha, (R_C^U)_\alpha] \quad (6.13)$$

Where R_C represents fuzzy rating of bridge component.

- Defuzzification of fuzzy rating of component R_c using centroid method.

$$\bar{x}_0 (\tilde{A}) = \frac{(x)_{\alpha_0}^U + (x)_{\alpha_n}^L + (x)_{\alpha_0}^L}{3} = \frac{(x)_{\alpha_0}^U + (x)_{\alpha_n}^U + (x)_{\alpha_0}^L}{3} \quad (6.14)$$

- The overall rating of the bridge, expressed as the bridge rating index (BRI), is calculated as the average of all component ratings, with equal weightage given to all components.

6.4.2 Flow chart

Figure 6.3 illustrates step by step procedure in form of flow chart for rating of bridge.

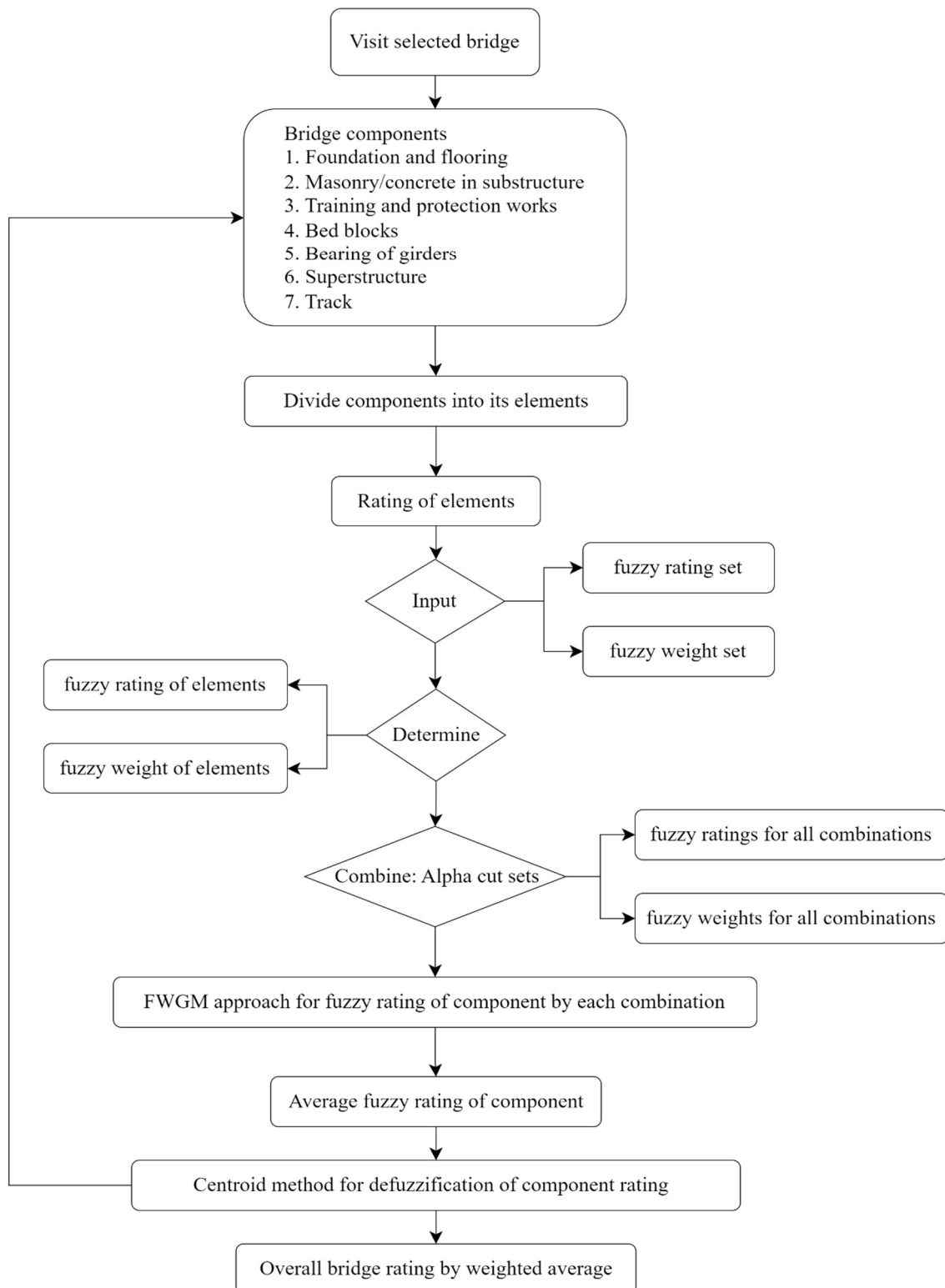


Figure 6.3: Flow diagram for bridge rating

6.5 Condition rating scale

6.5.1 Existing rating scale

Existing rating for condition assessment of railway bridges is listed in Table 6.1(a). Different components of a railway bridge are listed in Table 6.1(b).

Table 6.1(a): Existing rating for railway bridges (IRICEN 2014)

Rating	Description
5	Sound condition
4	a state that demands routine maintenance
3	a state that demands major or special repairs
2	a state that calls for planned reconstruction or rehabilitation.
1	a state that demands immediate reconstruction or rehabilitation.
0	Not inspected due to some reason
6	Not applicable for considered structure

Table 6.1(b): Railway bridge components (IRICEN 2014)

S. No.	Bridge components
1	Foundation
2	Substructure
3	Training and protection (T &P) works
4	Bed blocks
5	Bearing
6	Superstructure
7	Railway track

6.5.2 Proposed fuzzy rating scale

Table 6.2 and Table 6.3 provide linguistic term and description of fuzzy sets of rating and fuzzy set of weights or structural importance.

Table 6.2: Fuzzy rating for condition of member

Crisp rating	Fuzzy number	Condition	Description
10	(9,10,10)	Sound	No visible damage or deterioration.
9	(8,9,10)	Very good	Bridge is functioning without any performance degradation.
8	(7,8,9)	Good	Minor deterioration of secondary members of the bridge that does not affect the functionality of the bridge. Degraded members should be repaired.
7	(6,7,8)	Satisfactory	Major deterioration of secondary members of the bridge that may minorly affect the functionality of the bridge. Deteriorated members need to be repaired.
6	(5,6,7)	Poor	Minor deterioration of primary members of the bridge that affects the functionality of the bridge. Deteriorated members should be repaired soon.
5	(4,5,6)	Very poor	Damage or deterioration of one or two primary members of the bridge that significantly affects the functionality of the bridge. Degraded members should be retrofitted on priority basis.

4	(3,4,5)	Severe	Scheduled rehabilitation or retrofitting of overall bridge is required.
3	(2,3,4)	Very severe	Immediate rehabilitation or retrofitting of overall bridge is required.
2	(1,2,3)	Extreme	Scheduled reconstruction of bridge is needed.
1	(0,1,2)	Failed	Immediate reconstruction of bridge is needed.
	0	Skip/ Not inspected/ Not applicable	The element or component is not applicable or not inspected.

Table 6.3: Fuzzy weights for importance of elements

Fuzzy number	Linguistic term	Description
(0.75,1,1)	Very high	Defect on primary elements, that majorly affect structural performance
(0.50,0.75,1)	High	Defect on primary elements that minorly affect structural performance
(0.25,0.50,0.75)	Medium	Defect on primary elements that has degrade structural performance
(0,0.25,0.50)	Low	Defect on secondary elements that causes element failure
(0,0,0.25)	Very low	Defect on secondary elements that causes element degradation

Figure 6.4 provides fuzzy rating and its membership function. Figure 6.5 provides membership function of weights or structural importance.

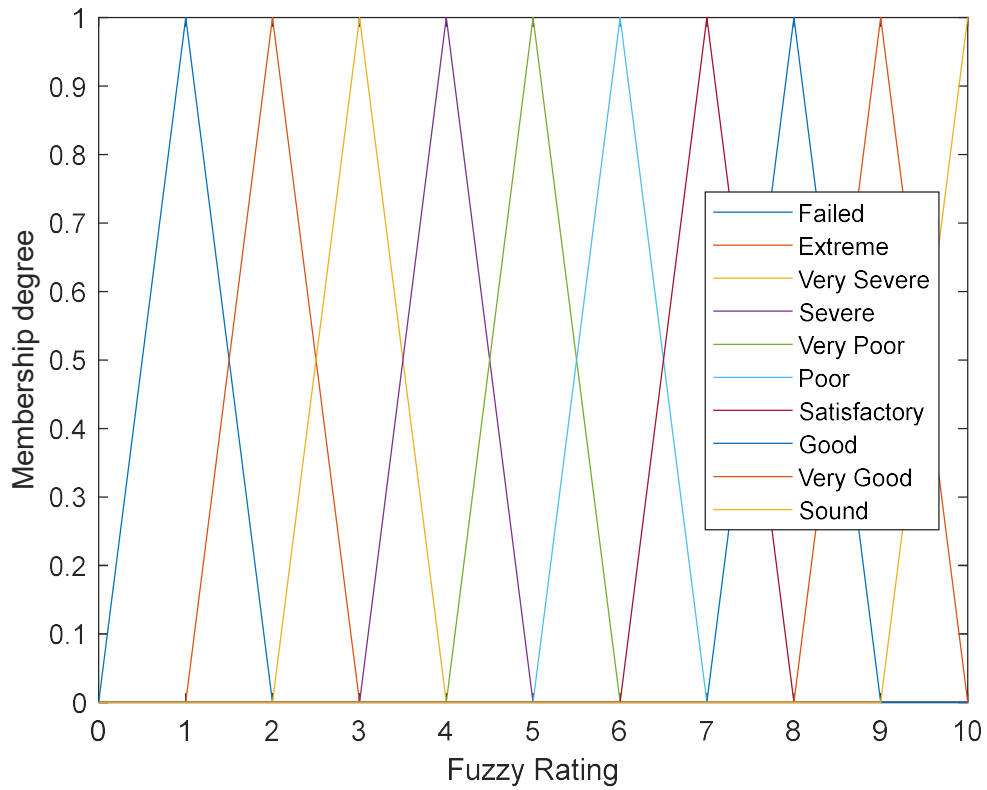


Figure 6.4: Fuzzy ratings with their membership functions (MF)

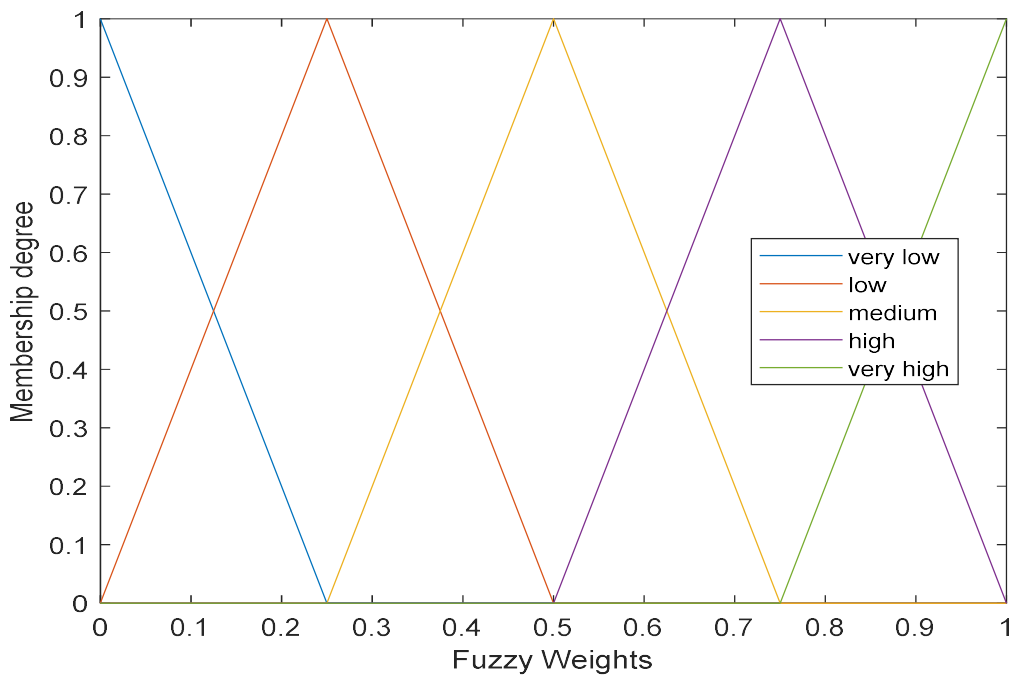


Figure 6.5: Fuzzy weights or structural importance with their MFs

6.6 Application

Only the visual assessment was performed by the authors as bridge experts for the goal of validating the proposed approach, i.e., to assess the condition of railway bridge components. Initially, visual inspection began to get the rating of the elements, followed by the rating of each bridge component, and lastly the total bridge rating, which is the study's main goal. Each bridge is made up of seven parts (Table 6.1(b)).

The number of inspected elements varies based on the kind and structure of the bridge. Case studies on some bridges were carried out, and the results were validated, as detailed below.

The authors personally visited and inspected all of the bridges in Case Studies 1, 2, and 3. The rating of the bridge according to (IRICEN 2014) is provided only by the authors. Because the worst component rating is used as the overall bridge rating. For example, if a bridge has three components with ratings of 4, 2, and 3, the overall rating number (ORN) of the bridge, according to IRICEN (2014), will be 2. The received bridge data was checked using our application, the data was entered by selecting options and inputting the requested information. Table 6.A1 provides snapshot of result obtained by developed application. Table 6.A2 provides summary of component rating and overall bridge rating obtained by existing method (IRICEN 2014) and proposed method.

Report generated by FBRs of case study-3 is presented in table 6.A1. Summary of rating bridge components of case study-1, 2, and 3 is listed in table 6.A2. according to existing and proposed rating system.

6.6.1 Case study-1

Road Over Bridge (ROB): Figure 6.6 shows the photograph of exiting road over bridge. The ROB is a balanced cantilever bridge located in Moradabad city, India.



Figure 6.6: Case study 1: Road Over Bridge (ROB)

Since worst component rating is taken as rating of overall bridge. ORN of the bridge as per IRICEN (2014) is 2, which indicates (Table 6.1) that bridge must be rebuilt or rehabilitated on a programmed basis. As per proposed approach, condition rating index of the bridge (BRI) is 3.43, indicating (Table 6.2) that bridge is in moderate to severe condition and should be replaced to function properly.

6.6.2 Case study-2

Steel Girder Bridge: Figure 6.7 shows the photograph of exiting railway bridge. The Bridge is a single-track solid web steel girder (Plate girder) bridge and overall length of 55m (3x18.30m). Bridge is located in Zafrabad-Jaunpur section, India.



Figure 6.7: Case study 2: Steel Girder Bridge

ORN of the bridge as per IRICEN (2014) is 3, which indicates (Table 6.1) that bridge requires major or special repair. However, according to proposed approach, bridge's condition rating index (BRI) is 8.32, which indicates (Table 6.2) that bridge is in good to very good condition and only requires routine or minor maintenance to serve its purpose.

6.6.3 Case study-3

Steel Truss Bridge: Figure 6.8 shows the photograph of existing steel truss railway bridge. Bridge is a single-track steel truss bridge with 6 spans of 30.48m each. More details of this bridge can be obtained in the reference (Patel and Pathak 2023).



Figure 6.8: Case study 3: Steel Truss Bridge

According to IRICEN (2014), bridge's ORN is 3, indicating (Table 6.1) that bridge requires major or special repair to serve its intended purpose. However, according to proposed approach, bridge's condition rating index (BRI) is 7.76, indicating (Table 6.2) that bridge is in good condition and only requires routine or minor maintenance.

6.6.4 Details of case study-3's component: T&P works

All steps of methodology are explained by taking example of elements of component: training and protection works (T& P works) of bridge case study 3. Table 6.B1 lists Crisp rating, fuzzy rating, and fuzzy weights for 2 elements/symptoms of component: Training and Protection (T&P) works. The next step in the proposed approach involves making all the combinations of fuzzy sets over all symptoms/elements used in the component. For the component, there are 2

symptoms and each symptom has 3 fuzzy rating sets associated to it, thus it makes a total of $2 \times 3 = 6$ fuzzy sets in total and the total number of combinations of these fuzzy sets is given by $3 \times 3 = 9$ combinations. Table 6.B2 show all the combinations of fuzzy rating and fuzzy weights obtained as per our methodology for the component (Eqn 6.9). The combinations are obtained by determining the lower and upper bounds of the MFs using the α -cuts. A set of α -cuts has an increment of 0.1 and ranges from 0 to 1. Table 6.B3 enumerates the α -cut sets of fuzzy ratings for each combination (Eqn 6.10). Table 6.B4 gives the α -cut sets of fuzzy weights or structural importance for each combination (Eqn 6.11). Table 6.B5 summarizes the rating value of the component: Training and Protection works, obtained by FWGM for all combinations (Eqn 6.12). Table 6.B6 presents final fuzzy value which is obtained by average of all combinations (Eqn 6.13). And then defuzzification of fuzzy component rating is done by centroid method (Eqn 6.14). Figure 6.B1 shows plot of component: T&P works for all 9 combinations according to data of Table 6.B5.

6.7 Concluding remarks

In order to ensure the safety of the people who depend on railway bridges as well as the functionality and mechanical stability of the infrastructure, it is imperative that these bridges be evaluated. Currently, there is no established systematic approach for assessing railway bridge conditions in India, including a comprehensive assessment of its elements through α -cut combinations.

Owing to the challenges associated with assessing bridge conditions, a thorough investigation was conducted, leading to the creation of an expert system. An algorithm based on the proposed methodology has been developed to rate bridge conditions. The process of evaluating bridges can be enhanced and improved with the help of this suggested approach. The approach accurately estimates the state of railway bridges in India by adopting a fuzzy logic strategy,

specifically an FWGM approach utilising fuzzy geometric mean and the centroid method. Visual expert assessments of the bridge elements were used to determine component ratings such as superstructure and substructure. The expert system's results closely match expert evaluations, proving the system's viability and applicability.

The findings indicate that this methodology can effectively handle various bridges with different components, elements, and rating scales. Consequently, the proposed methodology will greatly assist structural engineering experts and decision-makers involved in bridge management by providing a systematic and reliable approach for evaluating bridges and guiding future decisions regarding their recovery, rehabilitation, or demolition. The suggested 10-point rating system created to offer accurate evaluation grading, and it can be helpful in setting priorities for the routine maintenance and inspection of several bridges. As a result, it may be expanded to a large number of bridge networks and integrated with the Indian BMS to schedule and maintain records for inspection and maintenance tasks.

In conclusion, the newly developed expert system for analysing railway bridge problems appears to be an effective and appropriate tool for experts. The system is functional, versatile, and easily upgradeable as needed. It adds objectivity to the evaluation process and ensures assessment quality through model validation. While the system's implementation may be difficult and complex, it allows for an organised and systematic review of India's current railway bridge problems. By connecting with a Bridge Management System that keeps a database of all bridges in India, the model's results can be used in future research to define criteria for prioritising bridge inspections and maintenance actions.

Table 6.A1: Report of case study-3 obtained by FBRS

CONDITION RATING REPORT		
Bridge Details:		
Date - 30/10/2023		
Location\Section - Bareilly-Rampur section		
Division\Zone - Moradabad division (Northern Railway)		
Name & Number - Bridge-1077		
Type - Truss bridge		
No. of span x Length(m) - 6 x 30.48		

COMPONENT - MASONRY/CONCRETE IN SUBSTRUCTURE		
>> Element - Pier/abutment/ retaining walls /wing walls etc.		
o Loss of or Leaching of material	---	8
o Hollow sound on tapping	---	0
o Deterioration of surface, surface cracks	---	9
o Lateral tilt Differential	---	0
o Vertical cracks	---	0
o Longitudinal tilt (in the direction of track) or bulge	---	0
o Weep holes not functioning and no tilt or bulge	---	0
o Map pattern(surface) cracks in concrete, not progressive	---	7
o Deep & progressive cracks (in concrete)	---	0
o Longitudinal tilt	---	0
o Horizontal cracks	---	0
MASONRY/CONCRETE IN SUBSTRUCTURE RATING = 8.173		

COMPONENT - TRAINING AND PROTECTION WORKS		
>> Element - Training & Protection works		
o Pitching damaged or washed away	---	7
o Toe wall damaged or washed away	---	0
o Apron damaged or washed away	---	0
o Earth work section of guide bund/spur reduced	---	8
TRAINING AND PROTECTION WORKS RATING = 7.404		

COMPONENT - BED BLOCKS

>> Element - Bed block

o Crushing of bed block under bed plates	---	8
o Cracked bed block	---	6
o Cracks in masonry below bed block	---	0
o Loose/shaken bed-block	---	0

BED BLOCKS RATING = 7.016

COMPONENT - BEARING OF GIRDERS

>> Element - Roller & Rocker Bearing

o Corroded but not seized	---	8
o Corroded and seized	---	0
o Flattening of rollers (ovality)/ cracking	---	0
o Impact at bearing (floating)	---	0

BEARING OF GIRDERS RATING = 8.000

COMPONENT - SUPERSTRUCTURE

>> Element - Open Web Girders (truss/under slung)

o Weathered paint surface	---	8
o Flaking and peeling of steel	---	6
o Distortion of bracings	---	0
o Distortion of stiffeners	---	0
o Loose (field) rivets at floor system	---	0
o Loose (field) rivets at main chord joints	---	0
o Progressive loss of camber (needs to be reliably established)	---	0
o Vibration	---	8

SUPERSTRUCTURE RATING = 6.835

COMPONENT - TRACK

>> Element - Track

o Rail	---	10
o Sleeper	---	10
o steel trough	---	9

TRACK RATING = 9.171

XXXXX

END OF REPORT XXXXX

Table 6.A2: Rating of bridge components and overall bridge by existing and proposed method

S.No.	Bridge component	Case study 1- Road Over Bridge (ROB)		Case study 2- Steel Girder Bridge		Case study 3- Steel Truss Bridge	
		CRN (IRICEN 2014)	CCRI using FBRS	CRN (IRICEN 2014)	CCRI using FBRS	CRN (IRICEN 2014)	CCRI using FBRS
1	Foundation	0	0	0	0	0	0
2	Substructure	3	4.19	4	7.65	4	8.17
3	Training and protection (T &P) works	0	0	5	9.11	3	7.4
4	Bed blocks	2	2.74	5	9.21	3	7.02
5	Bearing	0	0	4	8	4	8
6	Superstructure	2	3.36	3	7.64	3	6.83
7	Track	0	0	0	0	5	9.17
Overall Bridge rating		2	3.43	3	8.32	3	7.76

Appendix-B

Table 6.B1: Crisp rating, fuzzy rating, and fuzzy weights for 2 elements/symptoms of component: Training and Protection (T &P) works of case study-3

Element/ Symptom	Crisp rating	Rating fuzzy set	weight fuzzy set
E1: Pitching damaged or washed away	7	5,6,7	0.75,1.0,1.0
		6,7,8	0.75,1.0,1.0
		7,8,9	0.75,1.0,1.0
E2: Earth work section of guide bund/spur reduced	8	6,7,8	0.5,0.75,1.0
		7,8,9	0.5,0.75,1.0
		8,9,10	0.5,0.75,1.0

Table 6.B2: Fuzzy ratings and fuzzy weights combinations

Combination (comb)	Element (E)	Fuzzy rating set	fuzzy weight set
comb1	E1	5,6,7	0.75,1.0,1.0
	E2	6,7,8	0.5,0.75,1.0
comb2	E1	5,6,7	0.75,1.0,1.0
	E2	7,8,9	0.5,0.75,1.0
comb3	E1	5,6,7	0.75,1.0,1.0
	E2	8,9,10	0.5,0.75,1.0
comb4	E1	6,7,8	0.75,1.0,1.0
	E2	6,7,8	0.5,0.75,1.0
comb5	E1	6,7,8	0.75,1.0,1.0
	E2	7,8,9	0.5,0.75,1.0
comb6	E1	6,7,8	0.75,1.0,1.0
	E2	8,9,10	0.5,0.75,1.0
comb7	E1	7,8,9	0.75,1.0,1.0
	E2	6,7,8	0.5,0.75,1.0
comb8	E1	7,8,9	0.75,1.0,1.0
	E2	7,8,9	0.5,0.75,1.0
comb9	E1	7,8,9	0.75,1.0,1.0
	E2	8,9,10	0.5,0.75,1.0

Table 6.B3: The α -cut sets of fuzzy ratings for each combination

	$(R_E^L)_\alpha$											$(R_E^U)_\alpha$										
α -cut	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
comb1	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0
	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0
comb2	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0
	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0
comb3	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0
	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0	9.0	9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0
comb4	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0
	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0
comb5	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0
	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0
comb6	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0
	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0	9.0	9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0
comb7	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0
	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0
comb8	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0
	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0
comb9	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0
	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0	9.0	9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0

Table 6.B4: The α -cut sets of fuzzy weights for each combination

	$(w_E^L)_\alpha$											$(w_E^U)_\alpha$										
α -cut	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
comb1	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb2	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb3	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb4	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb5	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb6	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb7	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb8	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00
comb9	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
	0.50	0.525	0.550	0.575	0.600	0.625	0.650	0.675	0.700	0.725	0.75	0.75	0.775	0.800	0.825	0.850	0.875	0.900	0.925	0.950	0.975	1.00

Table 6.B5: The rating value of the component: Training and Protection works, obtained by FWGM for all combinations

	$(R_C^L)_\alpha$											$(R_C^U)_\alpha$										
α -cut	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
comb1	5.38	5.48	5.59	5.69	5.79	5.90	6.00	6.10	6.20	6.31	6.41	6.41	6.52	6.63	6.73	6.84	6.95	7.06	7.16	7.27	7.38	7.48
comb2	5.72	5.83	5.94	6.04	6.15	6.26	6.37	6.47	6.58	6.68	6.79	6.79	6.90	7.02	7.14	7.25	7.37	7.48	7.60	7.71	7.82	7.94
comb3	6.03	6.15	6.26	6.37	6.48	6.59	6.70	6.81	6.92	7.03	7.14	7.14	7.26	7.39	7.51	7.64	7.76	7.88	8.00	8.13	8.25	8.37
comb4	6.00	6.10	6.20	6.30	6.40	6.50	6.60	6.70	6.80	6.90	7.00	7.00	7.10	7.20	7.30	7.40	7.50	7.60	7.70	7.80	7.90	8.00
comb5	6.38	6.49	6.59	6.69	6.80	6.90	7.00	7.10	7.21	7.31	7.41	7.41	7.52	7.63	7.74	7.84	7.95	8.06	8.17	8.27	8.38	8.49
comb6	6.73	6.84	6.95	7.06	7.16	7.27	7.37	7.48	7.59	7.69	7.80	7.80	7.91	8.03	8.14	8.26	8.37	8.49	8.60	8.72	8.83	8.94
comb7	6.58	6.68	6.77	6.87	6.97	7.07	7.16	7.26	7.36	7.46	7.56	7.56	7.65	7.74	7.83	7.92	8.02	8.11	8.20	8.30	8.39	8.49
comb8	7.00	7.10	7.20	7.30	7.40	7.50	7.60	7.70	7.80	7.90	8.00	8.00	8.10	8.20	8.30	8.40	8.50	8.60	8.70	8.80	8.90	9.00
comb9	7.38	7.49	7.59	7.70	7.80	7.90	8.00	8.11	8.21	8.31	8.41	8.41	8.52	8.63	8.74	8.85	8.95	9.06	9.17	9.27	9.38	9.49

Table 6.B6: Final fuzzy value (average of all combinations)

	$(R_C^L)_\alpha$											$(R_C^U)_\alpha$										
α -cut	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
	6.36	6.46	6.57	6.67	6.77	6.88	6.98	7.08	7.19	7.29	7.39	7.39	7.50	7.61	7.71	7.82	7.93	8.04	8.14	8.25	8.36	8.47

Final rating of component: training and protection works = $(6.36+7.39+8.47)/3 = 7.406$

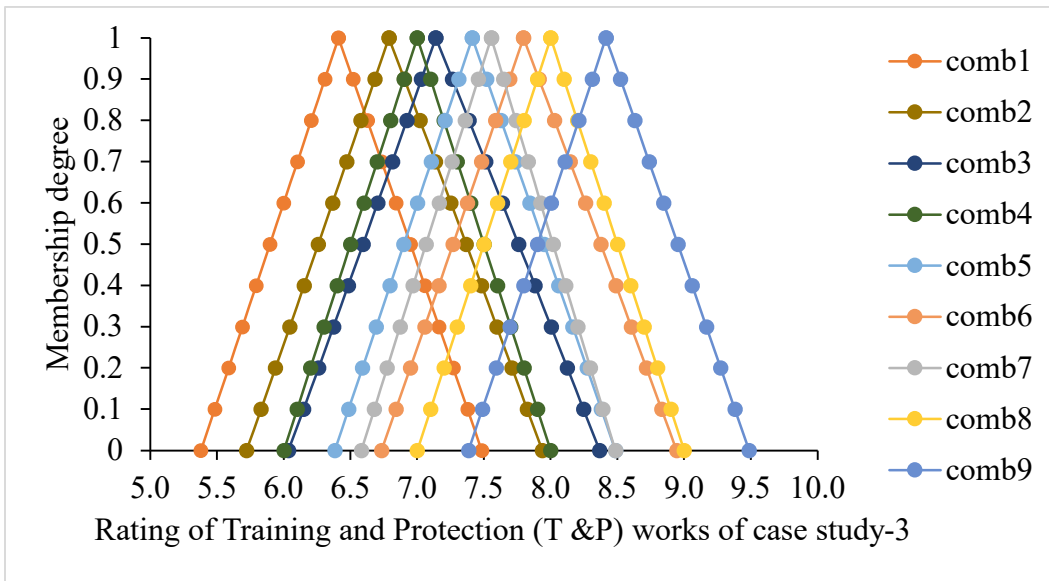


Figure 6.B1: Fuzzy rating numbers of all combinations