Fuzzy-Set based Treatment for FMEA in Optimum Metro-Vehicle Maintenance Strategy

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Abstract

It is obvious that in order to keep normal operation of a metro system, tremendous works are needed for its maintenance, nevertheless how to get optimum maintenance solution is still a critical problem to be solved. This paper presents a Fuzzy-Set based theoretical approach for verifying the reasonability of current methods in maintenance, determining whether a device or facility system should be removed from operation for repair while the "Failure Mode and Effects Analysis (FMEA)" is used. Under such case, fuzzy quantitative treatment is operated to the linguistic/semantic expression of the FMEA, which identifies the failure status of the sub-systems (or its components) with fuzzy quantitative information for evaluating its overall deterioration state. A case study of vehicles' maintenance in a metro network system in Shanghai is presented to show the applicability of the fuzzy treatment strategy to FMEA in the optimization of metro maintenance management.

Keywords: *Fuzzy set, failure mode and effects analysis, metro maintenance, optimization*

1. Introduction

Metro systems have been blooming up in recent half a century in the world and become the backbone of urban passenger transmission in many mega-cities such as New York in USA, London in UK, Shanghai in PRC, *etc*. People paid very concerns on the operation and management of a network metro system including maintenance, since the availability and service state of such metro systems will directly influence the normal activities of cities and their people to a great extent. As one of the most important aspects of metro system's operation and management, how to analyze and optimize the maintenance to support the operation of metro system will be the key issue of study in this paper.

As we know, researches on maintenance optimization models can be both qualitative and quantitative. The former includes techniques like TPM, RCM, *etc*. while the later incorporates various deterministic/ stochastic models like Markov Decision, Bayesian models, *etc*. [1, 2]. Although most of decision makings in maintenance are under uncertainty, fuzzy set theory is rarely applied [3, 4], mostly when discussing simple examples of fuzzy logic application in modeling rules of the so-called "approximate reasoning" (*i.e.*, "If the quality of maintenance is good, then the device reliability is high"; and "If the quality of maintenance is bad, then the device reliability is low). On the other hand, in order to examine the state of a device or installation system so that optimum maintenance strategies can be established, the technique of Failure Mode and Effects Analysis (FMEA) is introduced and a lot of research has been carried out to enhance the performance of FMEA in the past two decades. Bell *et al.*, [5] developed a method of causal reasoning in FMEA. The major advantages of the method are that reasoning is performed in terms of FMEA language. However, the method can be used only in cases where the input and output of a component are known. Another important work was done by Quin and Widera [6]. They proposed a method based on the theories of possibility distribution and probability of fuzzy events to treat uncertainties of the data and multiple failure modes. Nevertheless, the probability of fuzzy events must be known when using the method. Broadening the method in Ref. [7], Xu *et al.*, [8] presented a fuzzy-logic-based method for FMEA to address the interdependencies among various failure modes. However, the method is the so-called "approximate reasoning" and still mainly qualitative. Popovic *et al.*, [9] put forward an improved FMEA method and discussed its implementation into bus life cycle which provided a valuable reference to our study.

Recently, with rapid development of metro systems in the world especially in those highly populated areas, much more attentions are turning to researches on metro maintenance [10, 11, 12], nevertheless, few quantitative research achievement are mentioned or applied. It is believed that the main obstacle to quantitative researches is the modeling of linguistic/semantic information from FMEA about the state of the device or installation system as well as expert own knowledge. In other words, when researchers refer to maintenance of a device or installation system, special difficulties arise from the fact that some data are insufficiently precise or uncertain, while such data are often very important for maintenance decision making and must not be disregarded.

Aimed to give a possible solution to the issue above, the objective of this paper is to propose a Fuzzy-Set based quantitative approach for verifying the reasonability of current methods in maintenance, determining whether a device or facility system should be removed from operation for repair while FMEA is used. This paper is structured as follows. In "METHODOLOGY" section, starting with a necessary introduction to FMEA technique, the method of Fuzzy-Set based assessment for FMEA is presented, which is the quantitative tool of Fuzzy-Set based treatment for FMEA in optimum metro maintenance strategy. Then how the Fuzzy-Set based treatment for FMEA works to analyze and optimize the metro maintenance strategy is illustrated in detail. "CASE STUDY" section shows an application in which the proposed treatment method is applied to analysis and optimization for the strategy of metro-vehicle maintenance in Shanghai and the results are discussed in detail. Finally, "CONCLUSION" section summarizes this paper.

2. Methodologies

2.1. A word on FMEA

In recent years, the maintenance departments of some metro systems, where there are large pressures on repair, start to use the so-called FMEA to examine the reliability and safety state of a device or installation system, which is an important technique that is used to identify and eliminate known or potential failures to enhance reliability and safety of a simple product or even complex system. As we know, a device or installation system can be composed of several subsystems, which are made up of some components and become a hierarchical structure. FMEA is a bottom-up approach, starting with known failure modes at one level and investigate the effect on the next subsystem level. A complete analysis must span all the levels from components to the entire system.

However, there are still some limitations for conventional FMEA technique when it is applied into problem solving. The most important one among those limitations is that so much information in FMEA is expressed in the linguistic/semantic way such as 'likely', 'important' or 'very high', *etc*. In addition, most components or subsystems degrade over time and have multiple states. An assessment on these states is also often subjective and qualitatively described in natural language such as 'degradation of performance', 'reliability', and 'safety'. It is difficult for conventional FMEA to evaluate these linguistic variables. Furthermore, uncertainties and inaccuracies will be magnified to a large extent when analysis spans all the levels from components to the entire system if the assessment on states for each level is merely subjective and qualitative description.

This paper intends to develop a Fuzzy-Set based quantitative treatment method in order to enhance the performance of FMEA, which can reason fuzzy quantitatively in terms of the structure and language of FMEA level by level and consequently optimize the strategy of metro maintenance.

2.2. Fuzzy-set based assessment of FMEA

The essentials of this quantitative assessment method can be concluded as to quantify the vague information of device's deterioration degree through fuzzy inference and fuzzy evaluation, while human intelligence of inducing and deducting are fully used for processing this vague information.

With no loss of generality, define the subsystem set U of each deteriorative device which consists of n organized subsystems:

$$U = \{subsystem1, subsystem2, subsystem3, \ldots, subsystemn\} \quad (1)$$

Define the deterioration degree set V with five ranks, which are named VS (Very Severe), RS (Rather Severe), MD (Median), NG (Negligible), FF (Fault Free) respectively. And then we can have:

$$V = \{VS, RS, MD, NG, FF\} \quad (2)$$

Introducing Fuzzy Set Theory to describe the deterioration degree of the device, then the fuzzy relationship between U and V can be expressed by R, suppose n=5, we can have

$$R = \{r_{ij}\} \quad (i=1,2,\cdots,5;\ j=1,2,\cdots,5) \quad (3)$$

where

r_{ij} is the membership of *i*-th factor in the set of *U* corresponding to the *j*-th area of the set of *V*. It needs to be determined based on expert's knowledge and historical data, and the method can be referred to Ref. [13, 14].

Take *i*-th subsystem for example, $R_i = \{r_{i1}, r_{i2}, r_{i3}, r_{i4}, r_{i5}\}$ is used to represent the membership of *i*-th subsystem corresponding to five degree ranks. Therefore we can have:

A *i*=1, the deterioration of subsystem1 is median

$$R_1 = \{0.05, 0.20, 0.50, 0.20, 0.05\} \quad (4)$$

B *i*=2, subsystem2 is free from fault

$$R_2 = \{0.00,0.00,0.05,0.10,0.85\} \tag{5}$$

C *i*=3, the deterioration of subsystem3 is very severe

$$R_3 = \{0.85,0.10,0.05,0.00,0.00\} \tag{6}$$

D *i*=4, the deterioration of subsystem4 is light

$$R_4 = \{0.00,0.05,0.15,0.60,0.20\} \tag{7}$$

E *i*=5, the deterioration of subsystem5 is rather severe

$$R_5 = \{0.20,0.60,0.15,0.05,0.00\} \tag{8}$$

Then the fuzzy relationship matrix *R* can be expressed as following:

$$R = \{r_{ij}\} = \begin{Bmatrix} 0.05, & 0.20, & 0.50, & 0.20, & 0.05 \\ 0.00, & 0.00, & 0.05, & 0.10, & 0.85 \\ 0.85, & 0.10, & 0.05, & 0.00, & 0.00 \\ 0.00, & 0.05, & 0.15, & 0.60, & 0.20 \\ 0.20, & 0.60, & 0.15, & 0.05, & 0.00 \end{Bmatrix} \tag{9}$$

Moreover, the weights of subsystems are introduced as matrix *P*:

$$P = \{p_i\} \quad (i=1,2,\cdots,5) \tag{10}$$

$$\sum p_i = 1 \tag{11}$$

where

p_i is the weight of *i*-th subsystem.

The matrix *P* can be determined by the means of Analytic Hierarchy Process (AHP) [15, 16], whose advantage is to evaluate the relationship of various factors through “Pair Comparison (PC)”. The PC possesses the merit of more accuracy in dealing with the relationship of “one-by-one” rather than the “one-by-multiple”, thus avoiding the excessive assessment errors introduced by directly assessing multiple factors.

In this case, taking account of the influence of each subsystem to the entire device, we can assume the matrix *P* as follows:

$$P = \{0.20, \ 0.25, \ 0.30, \ 0.15, \ 0.10\} \tag{12}$$

The fuzzy comprehensive deterioration assessment vector *E* can be expressed by the multiplication of (9) and (12):

$$E = P \cdot R = \{0.20,\ 0.25,\ 0.30,\ 0.15,\ 0.10\} \cdot \begin{Bmatrix} 0.05, & 0.20, & 0.50, & 0.20, & 0.05 \\ 0.00, & 0.00, & 0.05, & 0.10, & 0.85 \\ 0.85, & 0.10, & 0.05, & 0.00, & 0.00 \\ 0.00, & 0.05, & 0.15, & 0.20, & 0.60 \\ 0.60, & 0.20, & 0.15, & 0.05, & 0.00 \end{Bmatrix} = \{\mathbf{0.3250}, 0.0975, 0.1650, 0.1000, 0.3125\}$$

Based on the calculation result above, the deterioration degree of the entire device can be determined by the so-called "Max-Membership Principle (MMP)" which defines that the max(E) area in deterioration degree set *V* represents the state of the entire device. In this case, as **max(E)=0.3250**, which is located in the first area VS (Very Severe) of deterioration degree set *V*, it means the entire device is in very serious condition and should be regarded as the wanted device for repair.

Though the above demonstrated the Fuzzy-Set assessment to the deterioration degree of a two-tier system, any multi-tier device or installation system can be assessed level by level in the same way.

2.3. How fuzzy-set based method works?

By the Fuzzy-Set based assessment above, the uncertain and vague information in FMEA can be quantified. So, we can calculate E_i of the past deteriorative device example *i*, and deposit a node at the area where the max(E_i) is located. Repeatedly calculate these past examples *i* (*i*=1, 2, …, *n*), and then there will be *n* nodes in Figure 1 separately distributed over five different areas of deterioration degree.

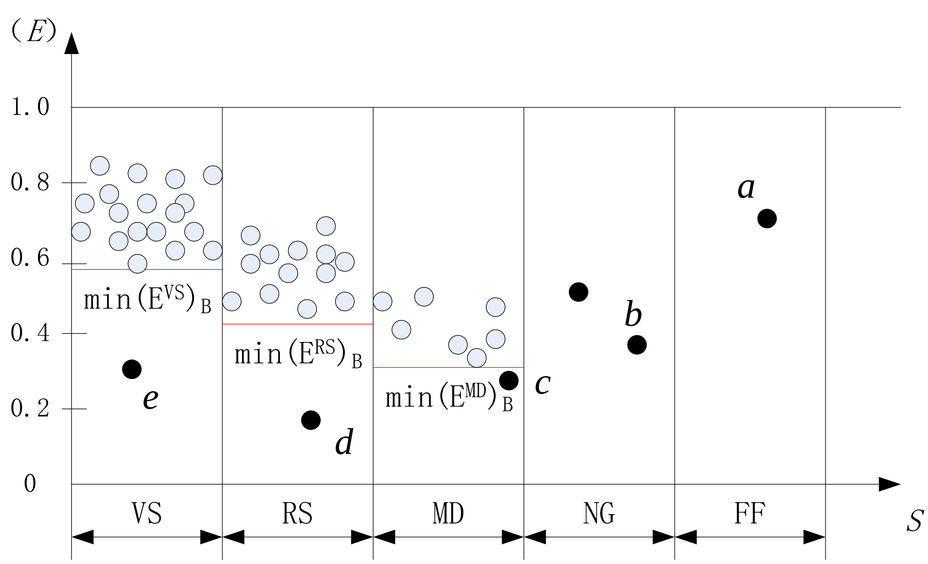

Figure 1. Results Distribution of Fuzzy-Set based Assessment to Past Examples

Based on the quantitative results above, the Fuzzy-Set based method will works to analyze and optimize the existing maintenance strategy as follows:

(1) Identifying the unreasonable decision-makings

According to Fuzzy Set Theory and the FMEA of a device or installation system in metro maintenance, if the past deteriorative device examples have been removed to be repaired, most of the corresponding nodes should be located in areas of VS (Very Severe) and RS (Rather Severe), and others will be located in area of MD (Median). Consequently, there are two kinds of nodes, which are considered to be unreasonable, as follows:

- The nodes which are located in areas of NG (Negligible) and FF (Fault Free), *i.e.*, node *a* and node *b*;
- The nodes which are far away from most of nodes in each area, i.e. node *c*, node *d* and node *e*.

Both kinds of nodes above are abnormal and the corresponding decision-makings need to be reviewed again.

(2) Determining the lower bounds to decision-makings

After those unreasonable nodes were found, those corresponding unreasonable decision-makings are reviewed carefully by the FMEA technique and re-evaluate the deterioration degrees of bottom components with Train Inspection Records (TIR). Then, past examples are re-calculated based on which the lower bounds to decision-making can be determined. These bounds are considered to be reasonable because they are derived from historical data of safe decision-makings to metro maintenance.

(3) Optimizing the existing metro maintenance strategy

Based on the bounds above, we can establish an optimum maintenance strategy and determine whether a deteriorative device needs to be removed from operation for repair. The optimized strategy is illustrated as follows:

- *if* max(E) is located in the areas of FF and NG, *then* the deteriorative device needs no repair;
- *if* max(E) is located in the area of MD and above the lower bounds $\min(E^{MD})_B$, *then* the deteriorative device needs repair;
- *if* max(E) is located in the area of RS and above the lower bounds $\min(E^{RS})_B$, *then* the deteriorative device needs repair;
- *if* max(E) is located in the area of VS and above the lower bounds $\min(E^{VS})_B$, *then* the deteriorative device needs repair.

In addition, it is noticed that the Fuzzy-Set based method for object deteriorative device mentioned above has fully take the advantages of internal regulation function enabling any fluctuation of membership in deterioration assessment will not be sensitively influence to the final fuzzy deterioration state assessment of the device or installation system.

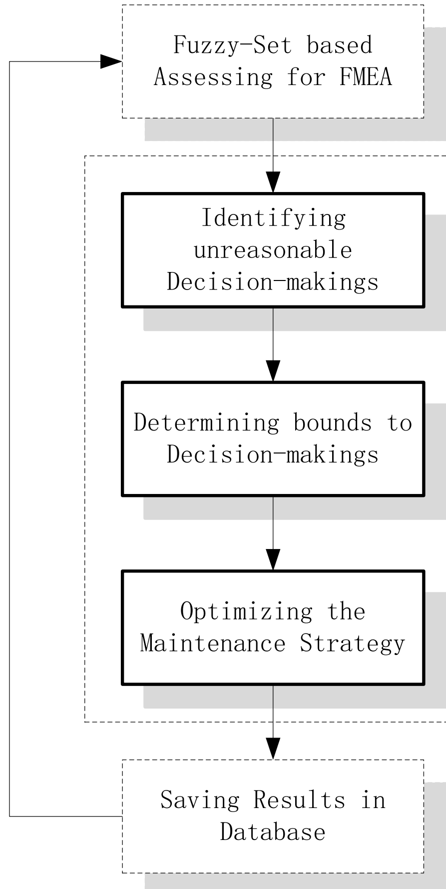

Figure 2. Work Flowchart of Fuzzy-Set based Method

3. A Case Study from Shanghai Metro System

3.1. Background

In this section, Shanghai Metro System in China is chosen for case study. As one of the largest and busiest metro systems in the world, Shanghai Metro keeps the scale of 11 lines, 287 stations and a total length of about 420 km, with more than 3000 vehicles. With rapid urban development, the current network of Shanghai Metro cannot adequately meet the city's transit demands, and consequently different from conventional solution, the task which the maintenance department has to fulfill is to maximize the number of operation trains with the constraint of limited vehicles. However, the existing strategy for metro vehicle maintenance in Shanghai Metro system is still based on experiential and qualitative method which results in either waste of cost or emergencies.

3.2. FMEA of metro train system

Within the existing Shanghai Metro System, an entire train will be detained for vehicle repair if its vehicles are so deteriorated that the train cannot operate normally. The overall deterioration state of a train which consists of the organized vehicles is examined by FMEA to enhance its reliability and durability.

The hierarchical structure of train FMEA is shown in Figure 3. As can be seen from the figure, there are five tiers and it is possible that a single component has multiple failure modes. For example, an analysis of bogie subsystem is shown in Table 1.

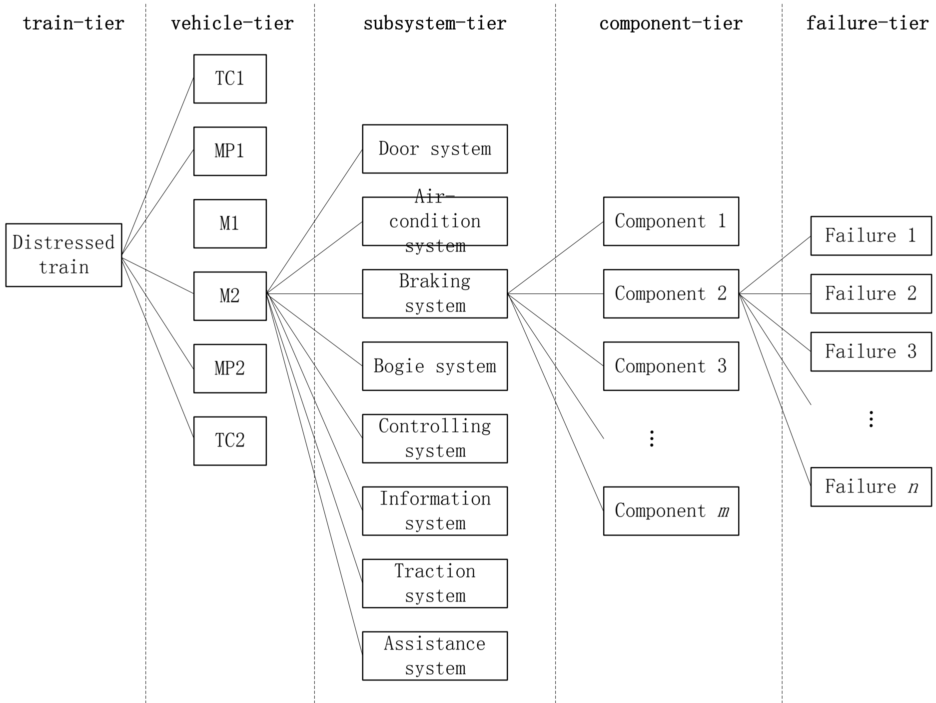

Figure 3. Hierarchical Structure of Train FMEA

Table 1. Bogie Subsystem FMEA (components and bogie subsystem)

Subsystem Code	Subsystem	Component Code	Component	Failure Mode	Effect
04	Bogie	0401001	Trailers frame	Surface of the frame cracked and injured	Frame injured and function loses
				Surface of the frame hanging connection has cracked	Frame injured and function is limited
				Frame hanging connection injured	Frame injured and function is limited
				Surface of the frame has scoring and contusion	Frame injured and function is limited
				The surface paint of the frame has crumbled off	The bogie is corroded
				Surface of the frame is corroded	Frame injured
		0403002	Trailer wheel set module	Wheel flange of the wheel set parameter exceeded	The train is unsteady and derails in operation
				Diameter of the wheel set parameter exceeded	The train is unsteady and derails in operation

				Surface of wheel set tread has defects	The train is unsteady and derails in operation
				Inner distance of the wheel set exceeded	Inner distance is too small and results in train's derailment in operation
				Surface of car axle body cracked	Car axle breaks
				Surface of car axle is corroded	Axle stress has defects
				Surface of car axle neck journal cracked	Neck journal of car axle breaks
				Shaft end injured	It is hard for bearing to rotate because of shaft end stress defect
		0402003	Taper spring	Rubber of cone spring cracked	Buffering function is reduced and the body is a slight imbalance
				Rubber of cone spring deformation	Buffering function is reduced and the body is a slight imbalance
				Rubber swell of cone spring exceeded	Cone spring function is reduced
				Rubber surface of cone spring was contaminated by oil	Some special oils make the properties of rubber material change
				Gasket for height adjustment of cone spring displacement, deformation, disappearance	Function loss
		0403009	Car axle box bearing	It is hard for bearing to rotate; the bearing cannot rotate	The bearing cannot rotate; shaft end wears off
				Bearing lubrication failure	Lubricating function failure; shaft end wears off; there is a risk of burn the axle
				Shaft end coordination failure	It is hard for bearing to rotate; shaft end wears off; there is a risk of burn the axle
				Lifting car protection ring break or cracked	Function loss
		0402005	Secondary spring	Rubber of air spring cracked	Reducing the security of air spring
				Rubber of air spring deformation)	Reducing the security of air spring
				Rubber swell of air spring exceeded	Reducing the security of air spring
				Rubber surface of air spring was contaminated by oil	Some special oils make the properties of rubber material change

		0402006	Altitude valve	Altitude valve leak	Gas path leak
				Altitude valve mechanical adjustment failure	Function failure
				Altitude valve pole rotation failure	Function failure
				Altitude valve safety sling away from the bogie	Function failure
		0402009	Anti-roll torsion bar joint bearing	Anti-roll torsion bar ball bearing failure	Hanger rod or torsion bar cannot rotate; anti-roll function disappears
		0405002	Traction block	Traction central rubber cones cracked	Reducing the security of rubber cones
				Traction central rubber cones deformated	Reducing the security of rubber cones
				Traction central rubber cones swell exceeded	Reducing the security of rubber cones
				Traction central elastic bearing failure	Cannot relieve the traction central gyroscopic force
		0405004	Piloting protection ring	Underbody lifting car protection bolt gap is too small	Protection bolt impacts frame in operation
		0405003	Elastic stopping gear 4T25	Lateral stopping gear spacing exceeded	Traction central module impacts frame in lateral direction
				Rubber stopping gear of lateral stopping gear injure or disappear	Central pin impacts frame in lateral direction then get injured
		0402001	Shock absorber（vertical）	Vertical shock absorber leaks	It cannot relieve vertical shock
				The bottom mount pad of vertical shock absorber cracked	Vertical shock absorber looses
		0402002	Lateral shock absorber	Lateral shock absorber leaks	It cannot relieve lateral shock

E_{ij} is defined to represent the fuzzy comprehensive deterioration assessment vector (*i* denote the number of a tier; *j* represent the number of component in *i*-th tier). Therefore, E_{ij} can be calculated by Fuzzy-Set based assessment for each tier of train FMEA and the final fuzzy comprehensive assessment vector for the deterioration state of the train can be obtained as fuzzy comprehensive assessment information propagate from the lower tier to the upper tier.

3.3. Fuzzy-set based assessment for train FMEA

Based on the FMEA of train system and the fuzzy quantitative assessment method proposed in this paper, a computer-aided system [17] for fuzzy assessment was developed. The main interface is shown in Figure 4.

Using the computer-aided system, 60 historical records of deteriorative trains which were removed from operation for repair and 30 historical records of deteriorative trains which were free from repair are calculated respectively. And the results are shown in Figure 5.

Figure 4. Main Interface of the Computer-Aided System

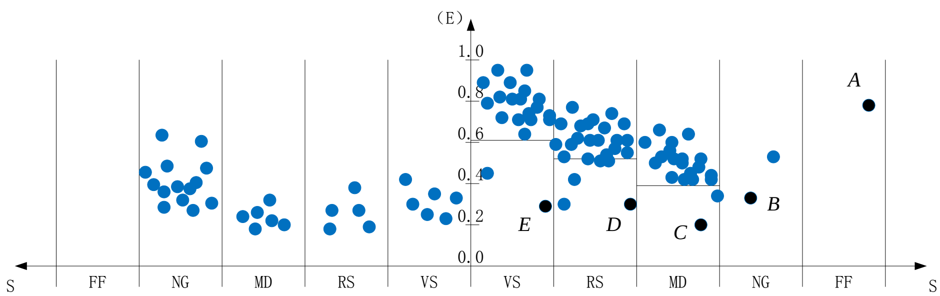

Figure 5. Fuzzy Object Deteriorative Train Distribution

3.4. Analysis and optimization to maintenance strategy

(1) Analysis to the unreasonable decision-makings

As shown in Figure 5, Fuzzy-Set based method has quantified the vague information of failure modes so that we can identify those unreasonable decision-makings out of the results, i.e. black nodes A, B, C, D and E.

Node A: It is obvious that Node A which is located in the area of FF, should be free from repair rather than to be detained for repair.

Node B: As the same to Node A, it is obvious that Node B which is located in the area of NG, should be free from repair rather than to be detained for repair.

Node C: It is necessary that Node C, which is far away from the most of nodes in the area of MD, should be reviewed once more.

Node D: As the same to Node C, it is necessary that Node D, which is far away from the most of nodes in the area of RS, should be reviewed once more.

Node E: As the same to Node C, It is necessary that Node E, which is far away from the most of nodes in the area of VS, should be reviewed once more.

Nodes for deteriorative trains free from repair: Most of the nodes for deteriorative trains free from repair are below those nodes for deteriorative trains to be repaired in the same area that implies there is a lower bound to decision-making of repair for deteriorative trains in each area.

(2) Determination of the lower bounds and decision-making of the train for maintenance

Based on the analysis above, those unreasonable decision-makings are reviewed carefully and re-calculated by fuzzy-set based method. From the calculation results, the lower bounds can be determined (Table 2).

Table 2. Lower Bounds to Decision Making

Area	VS	RS	MD	NG	FF
Lower bound	0.61	0.52	0.39	—	—

Based on the lower bounds, we can identify whether a deteriorative train needs to be detained for repair and another 10 past deteriorative train examples are listed in Table 3 in order to verify the applicability of the proposed method. As can be seen from the table, the fuzzy quantitative assessment is able to fit the reality. Moreover, other new inspection records of trains can be performed in a same manner. The experts' rule bases about matrix *R* and *P* can also be updated when more information of deteriorative trains is available. As a result, the assessment system will be continuously improved in a practical engineering environment.

Table 3. Verification of Cases by Fuzzy-Set based Assessment

No.	Train No.	Failure Mode	Max{E}	Membership	Decision-making in theory	Decision-making in practice	Verification
1	823	Open failure of TC1GNP reported by AGATE	VS	0.627	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
		Trigger board failure reported by TC2					
2	810	Three-phase over-current failure of air-compressor	VS	0.850	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
3	813	Replacement failure of TC1's mode handles	RS	0.568	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality

4	822	Oil leakage for two-axis gear of M2	MD	0.404	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
5	815	Display failure of DDU of TC2	VS	0.663	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
6	810	Air-spring leakage of MP2	MD	0.218	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
7	815	Relief failure of parking brake of M2	VS	0.176	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
8	824	1st air-conditioner display failure of TC1	MD	0.156	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
9	801	2nd air-conditioner display failure of TC1	MD	0.340	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
10	821	Display failure of DDU of TC1	MD	0.156	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality

3.5. Discussions

The above demonstrated a practical application of the proposed Fuzzy-Set based treatment for FMEA in optimum metro-vehicle maintenance. Furthermore, when the Fuzzy-Set based treatment works, it should be noticed that:

(1) The fuzzy quantitative assessment matrix $\{E\}$ could provide the membership among different degree region (*VS, RS, MD, NG, FF*), which is a strong decision-making support for determining whether a metro train should be detained for repair.

(2) The located region of $\max(E)$ could generally indicate the deterioration intensity of the metro train, meanwhile, membership of the $\max(E)$ can also represent the membership relation of the metro train to its located region (*VS, RS, MD, NG, FF*).

(3) Fuzzy-Set based assessment is a test of in-deterministic quantitative analysis, which can be used either in pre-feasibility study or in post-decision-making appraisal. It is verified that the quantitative fuzzy assessment to the max(*E*) location at the degree region (*VS, RS, MD, NG, FF*) is well correlated to the deterioration assessment of the metro train. However, the threshold of membership value for judgment is still uncertain and needs more case studies for its improvement.

4. Conclusions

In this paper, a tentative attempt at introducing Fuzzy Set Theory into quantitative analysis and optimization of metro maintenance strategy is presented. Some achievements are as follows:

(1) A method of Fuzzy-Set based assessment for FMEA is put forward firstly, which is able to quantify the linguistic/semantic and vague/uncertain information in FMEA;

(2) Based on the method above, a completed Fuzzy-Set based treatment for FMEA is established to analyze and optimize the strategies of metro-vehicle maintenance;

(3) Initial application into the vehicle maintenance of Shanghai Metro System shows, that the proposed method and treatment has a good performance and consequently is worth further development.

This study is helpful in theory and practice of metro maintenance and its methodology could be further applied into a broad family of facility group or system in other engineering fields.

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