A Computer Aided System for URT Maintenance Optimization Based on a FMEA - fuzzy Model

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Abstract: *In recent years, urban rail transit (URT) systems have rapidly developed in China, however, their existing strategies for vehicle maintenance are still based on experiential and qualitative methods which result in either high cost or emergencies. In this paper, a tentative attempt at introducing the fuzzy set theory into quantitative analysis and assessment of URT trains' failures was presented. Based on the proposed FMEA-fuzzy model, a computer aided system for URT maintenance optimization was developed. The overall structure and procedure of the system were described in detail, and the important issues, including the development environment, improvement to FMEA table, acquisition of weight distribution matrix P, and setting of fuzzy vector R, were also discussed. Initial application into the vehicle maintenance of Shanghai Metro System shows, that the proposed model and computer aided system have a good performance and consequently are worth further development.*

Key words: urban rail transit; maintenance; fuzzy set; failure mode and effects analysis (FMEA); computer aided system

1 Introduction

In recent years, with characteristics such as large carrying capacity, high-speed and safety, urban rail transit (URT) systems have gained rapid development in China. Particularly, the URT systems in several major cities, e. g. Beijing, Shanghai and Guangzhou, have successively entered into a new stage of network operation. In accordance with this situation, during promoting the scientific level of the URT train's maintenance, we have also experienced the transition from the preventive maintenance schedule which combines regular maintenance with periodic maintenance to the inspection and repairs schedule including both scheduled maintenance and state-based maintenance [1].

With the strategy of state-based maintenance, the time and scope of maintenance for URT vehicles is determined from the view of reliability, that is also called Reliability Centered Maintenance (RCM) [2,3]. In this case, we can achieve the goal to maximize the economic profit under a safety prerequisite. However, we should also raise a higher request in terms of test,

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analysis and personnel quality. On the other hand, most of the URT vehicles in Beijing, Shanghai and Guangzhou have been equipped with a self-diagnostic system and information system. With this equipment, the function and physical loss of the electronic and electrical system as well as the mechanical system can be monitored and controlled, thus providing a good environment for state-based maintenance.

As we known, research on maintenance optimization can be both qualitative and quantitative. The former includes techniques like TPM, RCM, etc. while the latter incorporates various deterministic/stochastic models like Markov Decision and Bayesian models, etc [4]. Although most decision making in maintenance is under uncertainty, fuzzy set theory is rarely applied when discussing simple examples of fuzzy logic application in modeling rules of the so-called "approximate reasoning". 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 researches have 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 Reference [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 a bus life cycle which provided a valuable reference to our study. Recently, with rapid development of metro systems in the world especially in highly populated areas, much more attention is turning to research on metro maintenance [10~12], nevertheless, few quantitative research achievements are mentioned or applied.

In this paper, with the strategy of state-based maintenance, a FMEA-fuzzy model was proposed, which can minimize the number of trains for repairing and maximizing the number of trains in operation as well as maintaining minimum repair cost under a safety prerequisite. Then a computer aided system for URT maintenance optimization was developed based on the FMEA-fuzzy model. Moreover, the important issues in developing the computer aided system were also discussed, including the development environment for the computer aided system, improvement to a FMEA table of URT vehicles, acquisition of weight distribution matrix P, and setting of the fuzzy vector R. Finally, a case study from the URT system in Shanghai shows the application and performance of the model and computer aided system proposed in this paper.

2 System deign

2.1 General structure

As a computer-aided decision-making system, the developed system consists of two basic functional modules and three subsidiary functional modules. The two basic functional modules include train deterioration assessment and basic information setting, and the three subsidiary functional modules include data storage, data input and output. Considering both the reusability and scalability of the whole system, these functional modules are designed in the principle of "high-cohesion and loose-coupling" to be the removable components. In this case, the main body of the system consists of five major modules including train deterioration assessment module, basic functional setting module, data storage module, data input module and data output module. Overall structure of the computer aided system is shown in Figure 1.

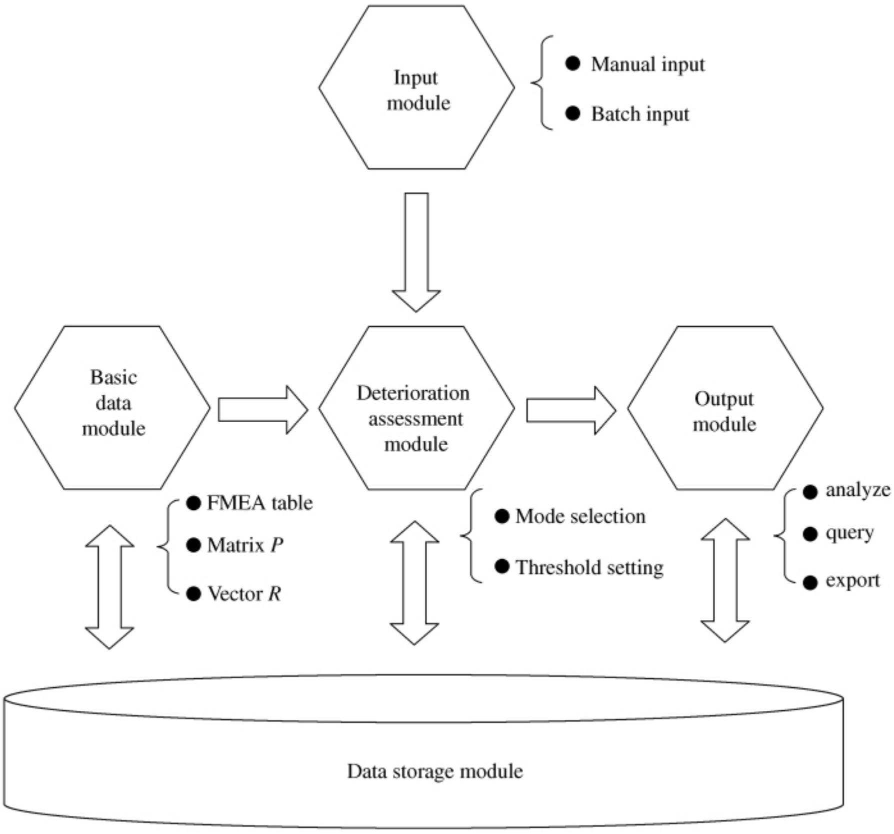

Figure 1 Overall structure of the computer aided system

The train deterioration assessment module is the core module of this system. Based on the FMEA-fuzzy model which embodies both the FMEA table and fuzzy comprehensive assessment, this module identifies the deterioration degree of each part, passes the deterioration degree through the tier structure of "part-subsystem-car-train", and finally gives a fuzzy comprehensive evaluation of the train's overall failure state. It has the following functions:

1) give a support to decision-making for detaining or releasing trains;

2) analyze the rationality of past decision-making behavior with historical records.

The basic information setting module, on the other hand, closely combined with the managerial characteristics of URT maintenance in China, can set the basic data structure for the comprehensive assessment according to the actual working conditions of URT maintenance. The basic data structure includes the train deterioration FMEA table, weight distribution matrix P and fuzzy vector R. It can also constantly adjust itself as needed. In addition, the data storage, input and output modules can, respectively, complete the functions of intermediate data storage, input and output of the records of examination as well as the analysis of operation results.

2.2 General procedure

The procedure of this system is basically in order to "basic data setting-information input-calculation-result output". Combined with the characteristics of URT maintenance, the general procedure of the computer aided system is designed and shown in Figure 2.

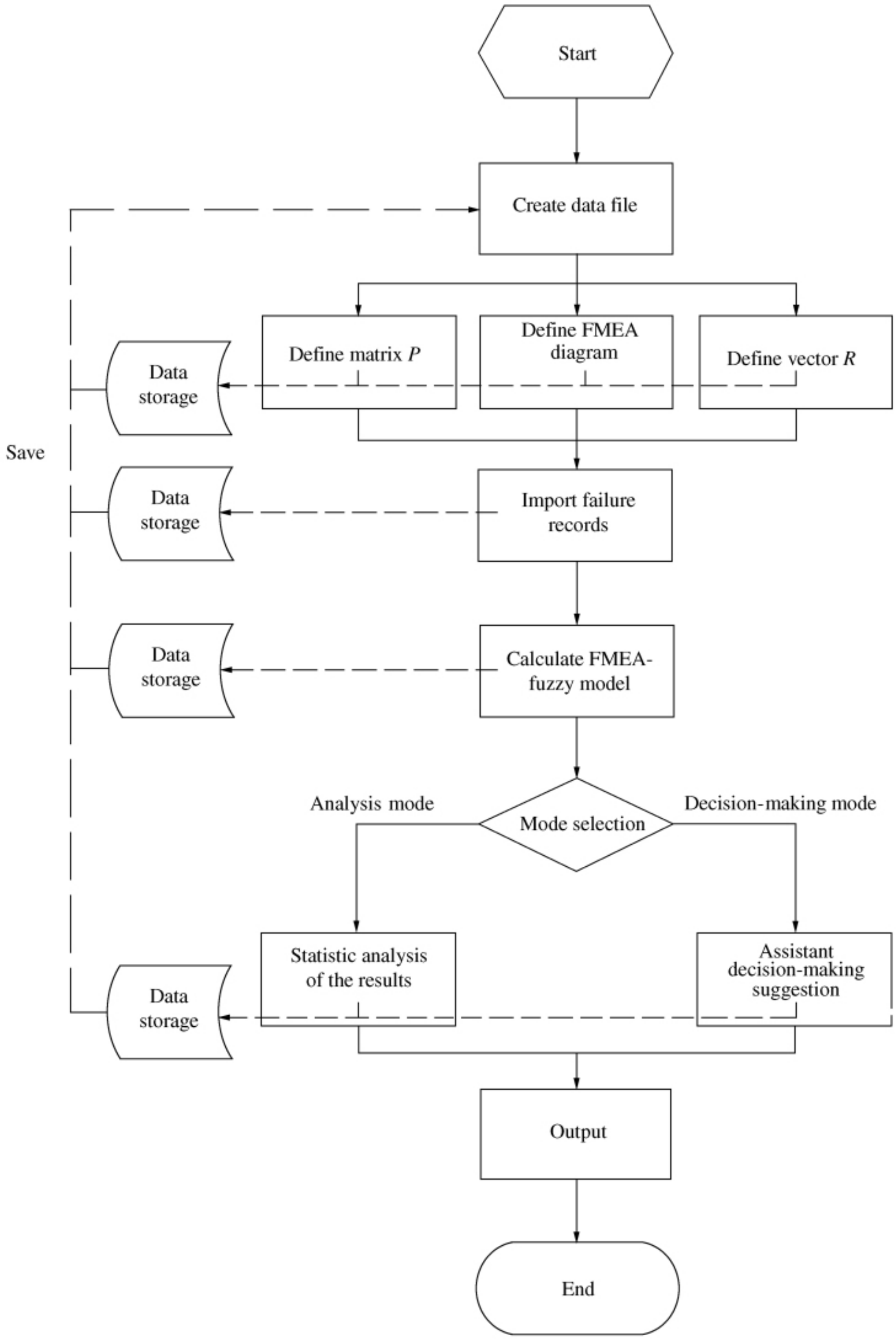

Figure 2 General procedure of the computer aided system

1) Create database files

This step mainly includes the importing of the train deterioration FMEA table, the setting of weight distribution matrix P and fuzzy vector R.

2) Input the records of examination

According to the need of managerial work of URT maintenance, there are two different modes including "decision-making mode" and "analysis mode". In the decision-making mode, the historical records of detaining or releasing trains about the deterioration information from the maintenance department are imported into the system. In the analysis mode, the records of deterioration information from the deterioration declaration system are imported into this system.

3) Comprehensively assess the deterioration degree based on the FMEA-fuzzy model

With the basic data from the database and the imported deterioration information in hand, by using the FMEA-fuzzy model to analyze and calculate the hazard of FMEA. In the analysis mode, perform the fuzzy quantitative assessment on the cause-effect information regarding different kinds of faults from the historical records of detaining or releasing trains. Meanwhile, analyze the rationality of detaining or releasing trains and decide the fuzzy thresholds. In the decision-making mode, perform the fuzzy quantitative assessment on the cause-effect information regarding different kinds of faults from the newly recorded history while using the fuzzy thresholds to decide the detaining or releasing of trains.

4) Output the results

Provide the assistant decision information for detaining or releasing trains according to the computed results and the threshold with its graphical presentation. Query the data of failure information and computed results through query controls in different forms and thus provides the information reports as needed.

2.3 FMEA-fuzzy modeling

2.3.1 Physical illustration of the FMEA-fuzzy model

It is our objective that a URT train system should perform its serviceability as much as possible, i. e., we intend to minimize the number of trains for repair and maximize the number of operational ones. The physical statement reads as follows:

1) For maintaining minimum repair cost, it is necessary to adopt the "state-based repair under safety prerequisite" principle.

2) Following to the FMEA rule, the distress causality of each component in each sub-system of the train is used for estimating the fuzzy information of the distress (default), such as Very Severe (VS), Rather Severe (RS), Median (MD), Negligible (NG) and Fault Free (FF).

3) The train distress system model is established based on a fuzzy appraisal of the causality between the default and the consequence, upon which the object distressed train identification criteria is founded.

2.3.2 Mathematical expression of the FMEA-fuzzy model

The essentials of the FMEA-fuzzy model can be concluded as to quantify the vague information of a train´s deterioration degree through fuzzy inference and fuzzy evaluation, while human intelligence of inducing and deducing are fully used for processing this vague information.

With no loss of generality, define the sub-system set U of each deteriorative train which consists of eight organized subsystems

$$U = \{U_1, U_2, U_3, U_4, U_5, U_6, U_7, U_8\} = \{\text{door system, air-condition system, braking system, controlling system, bogie system, information system, traction system, assistance system}\} \quad (1)$$

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. Then we can have:

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

Introducing the fuzzy set theory to describe the deterioration degree of the device, then the fuzzy relationship between U and V can be expressed by R, we can have

$$R = \{r_{ij}\}$$
$$(i = 1, 2, \cdots, 8;\ j = 1, 2, \cdots, 5) \quad (3)$$

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

Taking the 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:

1) $i = 1$, the deterioration of the door system is very severe

$$R_1 = \{0.85, 0.10, 0.05, 0.00, 0.00\} \quad (4)$$

2) $i = 2$, the deterioration of the air-condition system is light

$$R_2 = \{0.05, 0.20, 0.50, 0.20, 0.05\} \quad (5)$$

3) $i = 3$, the deterioration of the braking system is very severe

$$R_3 = \{0.85, 0.10, 0.05, 0.00, 0.00\} \quad (6)$$

4) $i = 4$, the deterioration of the controlling system is light

$$R_4 = \{0.00, 0.05, 0.15, 0.60, 0.20\} \quad (7)$$

5) $i = 5$, the bogie system is free from fault

$$R_5 = \{0.00, 0.00, 0.00, 0.00, 1.00\} \quad (8)$$

6) $i = 6$, the deterioration of the information system is light

$$R_6 = \{0.00, 0.05, 0.15, 0.60, 0.20\} \quad (9)$$

7) $i = 7$, the deterioration of the traction system is very severe

$$R_7 = \{0.85, 0.10, 0.05, 0.00, 0.00\} \quad (10)$$

8) $i = 8$, the deterioration of the assistant system is light

$$R_8 = \{0.00, 0.05, 0.15, 0.60, 0.20\} \quad (11)$$

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

$$R = \{r_{i,j}\} = \begin{bmatrix} 0.85 & 0.10 & 0.05 & 0.00 & 0.00 \\ 0.05 & 0.20 & 0.50 & 0.20 & 0.05 \\ 0.85 & 0.10 & 0.05 & 0.00 & 0.00 \\ 0.00 & 0.05 & 0.15 & 0.60 & 0.20 \\ 0.00 & 0.00 & 0.00 & 0.00 & 1.00 \\ 0.00 & 0.05 & 0.15 & 0.60 & 0.20 \\ 0.85 & 0.10 & 0.05 & 0.00 & 0.00 \\ 0.00 & 0.05 & 0.15 & 0.60 & 0.20 \end{bmatrix} \quad (12)$$

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

$$P = \{p_i\} \quad (i = 1, 2, \cdots, 8) \tag{13}$$

$$\sum p_i = 1 \tag{14}$$

Where P_i is the weight of the i-th subsystem.

The matrix P can be determined by the means of the 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 train, we can assume the matrix P as follows:

$$P = \{0.05, 0.05, 0.30, 0.10, 0.10, 0.10, 0.20, 0.10\} \tag{15}$$

The fuzzy comprehensive deterioration assessment vector E can be expressed by the multiplication of Equation (12) and Equation (15):

$$E = P \cdot R = \{0.05, 0.05, 0.30, 0.10, 0.10, 0.10, 0.20, 0.10\} \cdot \begin{Bmatrix} 0.85 & 0.10 & 0.05 & 0.00 & 0.00 \\ 0.05 & 0.20 & 0.50 & 0.20 & 0.05 \\ 0.85 & 0.10 & 0.05 & 0.00 & 0.00 \\ 0.00 & 0.05 & 0.15 & 0.60 & 0.20 \\ 0.00 & 0.00 & 0.00 & 0.00 & 1.00 \\ 0.00 & 0.05 & 0.15 & 0.60 & 0.20 \\ 0.85 & 0.10 & 0.05 & 0.00 & 0.00 \\ 0.00 & 0.05 & 0.15 & 0.60 & 0.20 \end{Bmatrix} =$$

$$\{0.470, 0.080, 0.098, 0.090, 0.163\}$$

Based on the calculation results above, the deterioration degree of the entire train 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 train. In this case, as max(E) = 0.470, which is located in the first area VS (Very Severe) of deterioration degree set V, it means the entire train is in a very serious condition and should be regarded as wanted for repair.

2.3.3 Decision-making criterion for detaining or releasing trains

Based on the FMEA-fuzzy model proposed above, a decision-making criterion for detaining or releasing trains can be developed. The decision-making criterion can be described as follows:

Step 1 Comprehensively assess the past records based on the FMEA-fuzzy model and obtained the thresholds for train detaining or releasing.

Step 2 Decided whether a damaged train should be detained or released according to the thresholds for train detaining or releasing.

1) Thresholds for train detaining or releasing

It is noticed that the fuzzy identification for the distressed train mentioned above has fully taken the advantages of an internal regulation function enabling any fluctuation of membership in distress assessment will not be sensitively influenced to a final fuzzy distress state assessment of the train.

Calculate E_i of the past distressed train example i, and deposit a node at the area where the Max(E_i) is located. Repeatedly calculate past examples $i = 1, 2, \cdots, n$, and then there will be n nodes in Figure 3, separately distributed over five different areas. Setting upper and lower bounds in each area, then they could be shown as Max (E^{VS}) $_R$ (lower suffix R means repair) , Min (E^{VS}) $_R$, Max(E^{RS}) $_R$, Min (E^{RS}) $_R$, Max(E^{MD}) $_R$, and Min(E^{MD}) $_R$ in area VS, RS, MD, respectively. It is recognized that Max (E^{NG}) $_R$, Min(E^{NG}) $_R$, Max (E^{FF}) $_R$, and Min (E^{FF}) $_R$ should be zero. In contrast, in Figure 4, fuzzy distribution of past distressed trains which are free from repair is also presented, in which symbol Max(E^{NG}) $_F$ (lower suffix F means free from repair) , Min (E^{NG}) $_F$, Max(E^{MD}) $_F$, Min (E^{MD}) $_F$, Max (E^{RS}) $_F$, and Min(E^{RS}) $_F$, Max(E^{VS}) $_F$, Min(E^{VS}) $_F$ represented the upper and lower boundsin area NG, MD, RS, VS respectively.

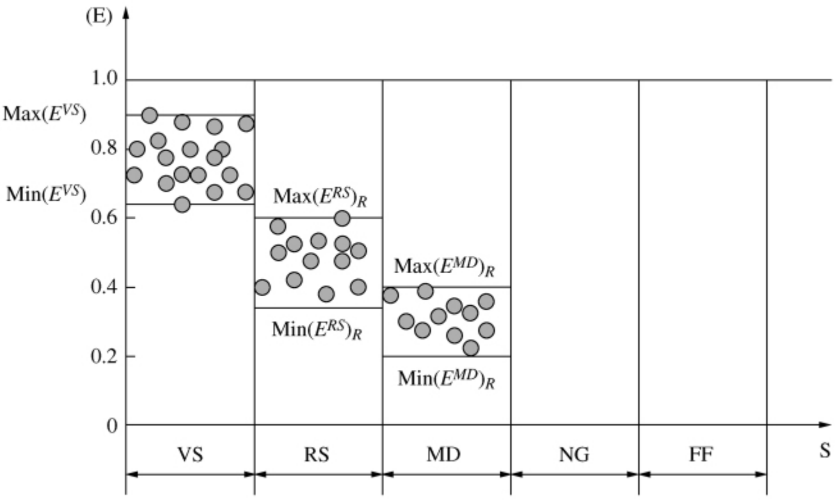

Figure 3 Fuzzy distribution of distressed trains for repair

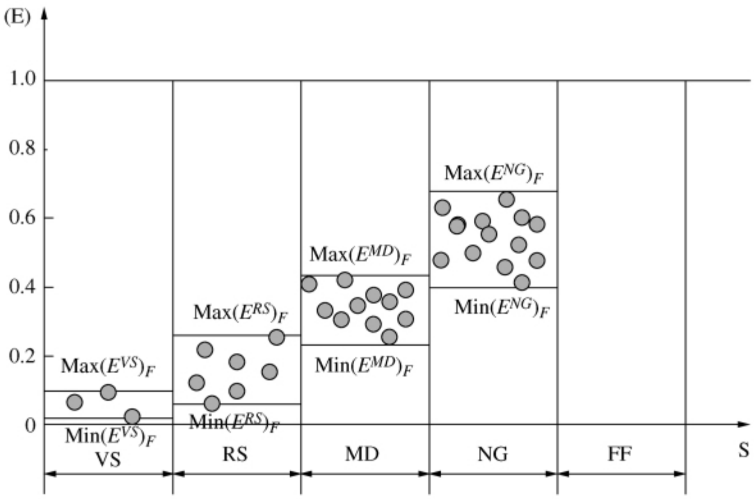

Figure 4 Fuzzy distribution of distressed trains free from repair

2) Decision-making criterion for train detaining or releasing

Therefore, the procedure and criteria to identify whether a distressed train is one for repair can be presented as following:

(1) Calculate fuzzy comprehensive assessment matrix E and find the area where $\mathrm{Max}(E) = (E)$ is located;

(2) If $\mathrm{Max}(E) = (E)$ of the distressed train is located in area VS, compare the VS area in Figure 3 and Figure 4 and we have:

① if $(E) < \mathrm{Min}(E^{VS})_R$, it will be free from repair;
② for the train under repair if its $\mathrm{Max}(E^{VS})_R > (E) > \mathrm{Min}(E^{VS})_R$ and $\mathrm{Max}(E^{VS})_F > \mathrm{Min}(E^{VS})_R$, then it will be free from repair.

(3) If $\mathrm{Max}(E) = (E)$ of the distressed train is located in area RS, compared RS area in Figure 3 and Figure 4 and we have:

① if $(E) < \mathrm{Min}(E^{RS})_R$, the distressed train is free from repair;
② if $\mathrm{Max}(E^{RS})_R > (E) > \mathrm{Min}(E^{RS})_R$ and $\mathrm{Max}(E^{RS})_F > \mathrm{Min}(E^{RS})_R$, then the distressed train with $[\mathrm{Max}(E^{RS})_F - \mathrm{Min}(E^{RS})_R]$ could be released, i. e., all distressed device with $(E) < \mathrm{Max}(E^{RS})_F$ should be free from repair;
③ if $(E) > \mathrm{Max}(E^{RS})_F$, it is a train for repair;
④ if $(E) > \mathrm{Max}(E^{RS})_R$, it is a train for repair;
⑤ the object trains with $[\mathrm{Max}(E^{RS})_F - \mathrm{Min}(E^{RS})_R]$ can be released, i. e., all distressed trains with $(E) < \mathrm{Max}(E^{VS})_F$ can be free from repair.

(4) If $\mathrm{Max}(E) = (E)$ of the distressed train is located in area MD, compared MD area in Figure 3 and Figure 4 and we have:
① if $(E) < \mathrm{Min}(E^{MD})_R$, the distressed train is free from repair;
② if $\mathrm{Max}(E^{MD})_R > (E) > \mathrm{Min}(E^{MD})_R$ and $\mathrm{Max}(E^{MD})_F > \mathrm{Min}(E^{MD})_R$, the object distressed trains with $[\mathrm{Max}(E^{MD})_F - \mathrm{Min}(E^{MD})_R]$ can be released, i. e., the distressed trains with $(E) < \mathrm{Max}(E^{MD})_F$ can be released;
③ if $(E) > \mathrm{Max}(E^{MD})_F$, the distressed train is an object for repair;
④ if $(E) > \mathrm{Max}(E^{MD})_R$, the distressed train is an object for repair.

(5) if $\mathrm{Max}(E) = (E)$ of the distressed train is located in area NG, compared NG area in Figure 3 and Figure 4 and we have:
① if $(E) < \mathrm{Max}(E^{NG})_R$, the distressed train is free from repair;
② if $(E) > \mathrm{Max}(E^{NG})_R$, the distressed train is an object for repair.

3 System implementations

3.1 Development environment

This computer-aided system was developed by the most widely used WINDOWS (2000/XP/Win7) operating system as the basic platform. Microsoft Access was also chosen as its database management platform and the system is implemented with the application of C# programming language in a Visual Studio integrated development environment.

3.2 Improvement to FMEA table

One of the keys of the FMEA-fuzzy model is the combination of fuzzy methods in the fuzzy set theory with the FMEA table. Since the fuzzy methods deal with continuous fuzzy information while the FMEA table deals with discrete deterioration assessment information, it is necessary to appropriately improve both the fuzzy method and FMEA table so that they can fit each other well. In this way, the transfer of fuzzy information through layers on the basis of the framework of the FMEA table can be realized. Therefore, the objective of unifying the decision-making criterion for train releasing with the fuzzy method can be achieved.

There are two improvements to the existing FMEA table:

1) Redefine the effects ranks of failures. Since the description of the original effects ranks cannot meet

the processing demand of the fuzzy method, the effects ranks should be redefined according to the deterioration degree of functions in contained parts.

2) Simplify the original FMEA table. Delete unnecessary information from the original table and the simplified table includes the following fields (Table 1): CarCode, CarName, SubsystemCode, SubsystemName, PartCode, PartName, Failure, Impact, Rank, Responce.

Table 1 Simplified FMEA Table

CarCode	CarName	Subsystem Code	Subsystem Name	PartCode	PartName	Failure	Impact	Rank	Responce

3.3 Acquisition of weight distribution matrix *P*

In order to implement the upward transmission of fuzzy deterioration information from the level of parts to the level of the whole train, it is necessary to determine the corresponding weight distribution coefficient p_{ij} for the effects of the functional deterioration of the elements on their upper elements´ function in the FMEA table.

The value of the coefficient p_{ij} is between 0 and 1. It can be achieved by the Analytic Hierarchy Process (AHP) using "Pairs Comparison (PC)" with the experience of the repair workers in URT systems.

3.4 Setting of fuzzy vector *R*

In the process of implementing this computer-aided system, there are five ranks of effects depending on the deterioration degree towards the function. They are Rank I (very severe), Rank II (rather severe), Rank III (median), Rank IV (negligible), and Rank V (fault free). In details, we can have:

1) The very severe fault VS (ranking I) represents that the fault has extremely serious effects on the functions. The value of fault fuzzy vector

$$R^{VS} = \{0.85, 0.1, 0.05, 0.00, 0.00\}$$

2) The rather severe fault RS (ranking II) represents that the fault has relatively serious effects on the functions. The value of fault fuzzy vector

$$R^{RS} = \{0.6, 0.2, 0.15, 0.05, 0.00\}$$

3) The median damage fault MD (ranking III) represents that the fault has median effects on the functions. The value of fault fuzzy vector

$$R^{MD} = \{0.05, 0.20, 0.50, 0.20, 0.05\}$$

4) The negligible fault NG (ranking IV) represents that the fault has negligible effects on the functions. The value of fault fuzzy vector

$$R^{NG} = \{0, 0.05, 0.15, 0.60, 0.2\}$$

5) The fault-free condition (ranking V) represents that there is absolutely no fault at all. The value of fault fuzzy vector

$$R^{FF} = \{0.00, 0.00, 0.00, 0.00, 1.00\}$$

The values of the failure fuzzy vectors are decided by the analysis of case data from the URT maintenance department. However, because of the inner regulatory function of the fuzzy set theory, the actual value can be adjusted in according to the situations in practice.

4 Case study

In this section, the metro system of Shanghai in China is chosen for our case study. Based on the FMEA of the train system and the FMEA-fuzzy model proposed in this paper, the computer-aided system was developed. The main interface of the computer-aided system is shown in Figure 5.

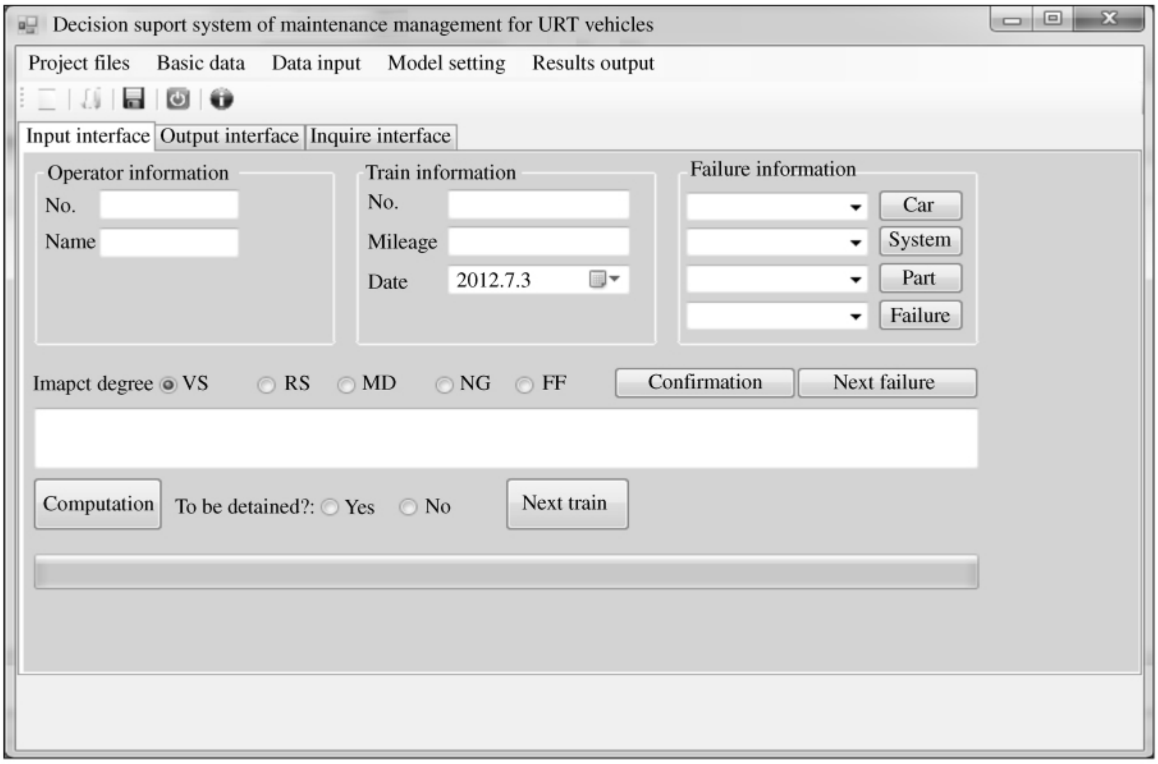

Figure 5 Main interface of the computer-aided system

Using the computer-aided system, 50 historical records of deteriorative trains which were removed from operation for repair and 50 historical records of deteriorative trains which were free from repair are calculated, respectively. 45 records from each 50 historical records were chosen for analysis mode and the rest are for the decision-making mode.

4.1 Calculation of the thresholds for train detaining or releasing based on historical records

According to 45 historical records for detaining trains and 45 historical records for releasing trains, fuzzy vectors R_{ij}($i = 1, 2, \cdots, 8$; $j = 1, 2, \cdots, 5$; $k = 1, 2, \cdots, 50$) can be given for 90 formulas, respectively. The fuzzy quantitative assessment matrix $\{E_k\}$ is the product of weight distribution matrix $\{P_k\}$ and fuzzy vector matrix $\{R_k\}$. After calculated by the analysis mode of the computer-aided system, the fuzzy comprehensive assessment matrix E can be obtained. The thresholds for train detaining or releasing are shown in Table 2 and the results are shown in Figure 6.

Table 2 The thresholds for detaining or releasing trains

Calculation results	Detaining					Releasing				
	VS	RS	MD	NG	FF	VS	RS	MD	NG	FF
Upper bound	0.663	0.524	0.413	——	——	0.476	0.416	0.486	0.726	——
Lower bound	0.336	0.392	0.276	——	——	0.371	0.312	0.395	0.457	——

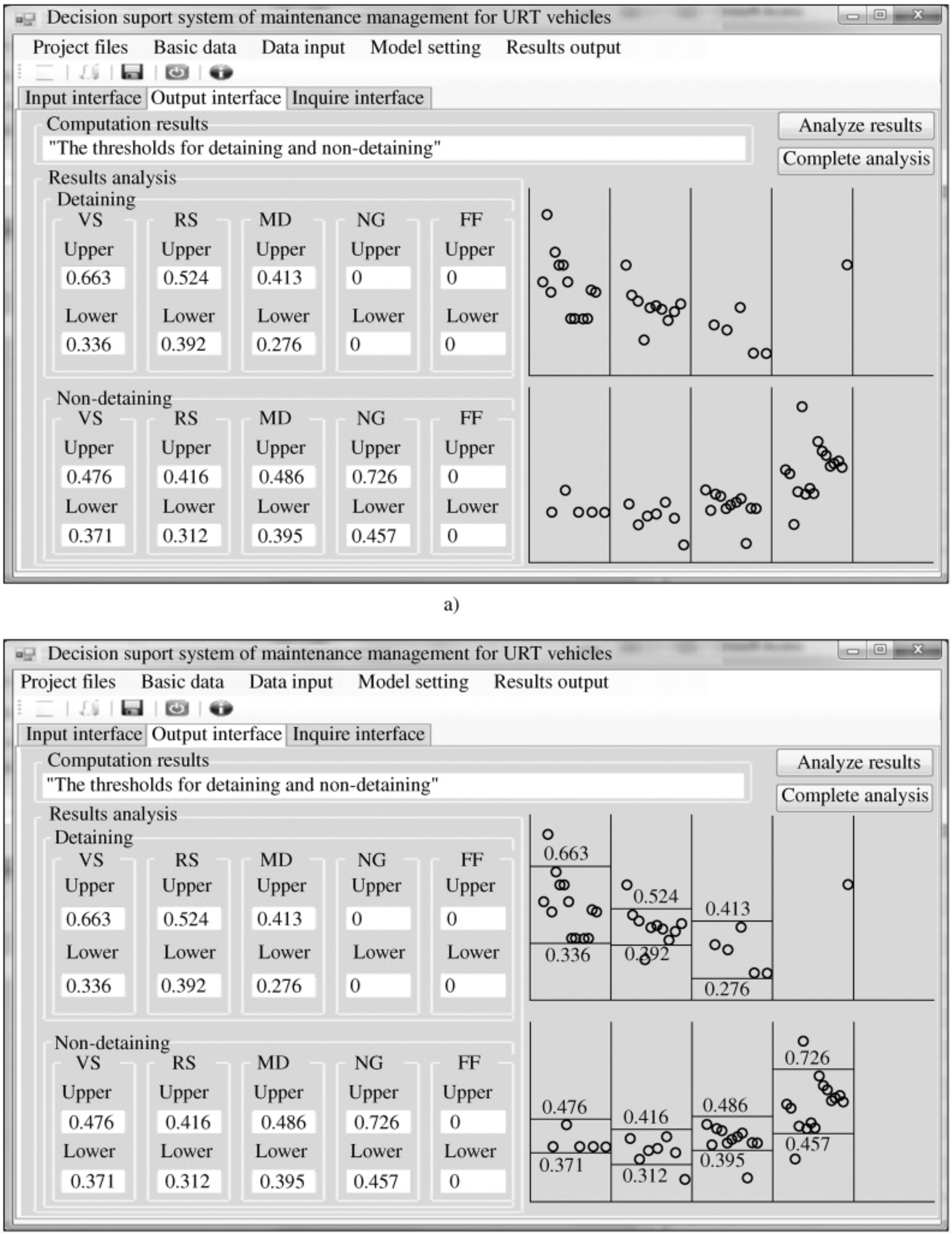

Figure 6 The output interface of the thresholds for detaining or releasing trains

4.2 Verification of cases for decision-making criterion based on the FMEA-fuzzy model

Based on the bounds (or thresholds), 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 model and computer-aided system. 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 the 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 computer-aided system will be continuously improved in a practical engineering environment.

Table 3 Verification of cases for decision-making criterion based on the FMEA-fuzzy model

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 Trigger board failure reported by TC2	VS	0. 517	Need to be detained	Had been detained	Fuzzy quantitative assessment fits the reality
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. 468	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. 304	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. 390	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

The above demonstrated a practical application of the proposed FMEA-fuzzy and computer-aided system in optimum metro-vehicle maintenance. Furthermore, when the model and system works, it should be noticed that:

1) The fuzzy quantitative assessment matrix $\{E\}$ could provide the membership among different degree regions (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 a pre-feasibility study or in a post-decision-making appraisal. It is verified that the quantitative fuzzy assessment to the max(E) location at the degree regions (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.

5 Conclusions

With the rapid development of URT systems in recent years, their maintenance have been experiencing the transition from the preventive maintenance schedule which combines regular maintenance with periodic maintenance to the inspection and repair schedule including both scheduled maintenance and state-based maintenance. However, their existing strategies for vehicle maintenance are still based on experiential and qualitative method which results in either high cost or emergencies. In this paper, a tentative attempt at introducing the fuzzy set theory into quantitative analysis and assessment of URT trains′ failures is presented. Based on the proposed FMEA-fuzzy model, a computer aided system for URT maintenance optimization was developed. Initial application into the vehicle maintenance of the Shanghai Metro System shows that the proposed model and computer aided system have a good performance and consequently are worth further development.

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