Reliability analysis of ballast cleaning device based on fuzzy FTA and FMEA

J Wang, Z X Cui*, S D Li, T Yang, H Y Cheng and R S Na
School of Mechanical Engineering, Inner Mongolia University of Technology, Hohhot, 010051, P.R. China
E-mail: cuizhaoxia73@163.com

Abstract. On the basis of analyzing the fault tree diagram of the ballast cleaning device of railway switch ballast cleaning machine, the fuzzy fault tree of the ballast cleaning device is established by blurring the probability of bottom event. Introducing grey fuzzy analysis correlation method, using the normal fuzzy comprehensive evaluation method of combining the theory and experts, quantitative and qualitative analysis, the fuzzy fault tree based on fault tree's minimum cut sets, the fuzzy importance degree of the basic events, calculation of each failure mode and the top event correlation, figure out the influence of the top event to occur to the larger events and failure mode. Then FMEA method is used to analyze the key parts of ballast cleaning device such as gripper and sprocket, and corresponding compensation measures are put forward according to the specific failure reasons.

1. Introduction
In the process of ballast cleaning of railway turnout, the ballast cleaning mechanism is in direct collision contact with the ballast, which is very complex to bear load. As a result, each component of the ballast cleaning mechanism needs to meet stronger comprehensive performance such as strength, stiffness and impact resistance. Once the fault can’t be completed within the specified time ballast cleaning work, thereby affecting the use of railway section causing a heavy loss.

Since the turnout ballast leaner designed in this paper belongs to the research and development stage, the fault data of railway sieve cleaner is very deficient, and the accurate value of bottom event probability cannot be obtained. In view of the lack of reliability data and the difficulty in obtaining fault data, many scholars have proposed and applied some new reliability solving methods. When analyzing structural failure, Jihyun Park introduces expert scoring method on the basis of FMEA to obtain the failure mode of structure [1].Sohag Kabir et al. summarized the prospect of fuzzy theory in solving uncertainty problems in reliability engineering [2].Based on the traditional fault tree, some scholars introduced normal fuzzy Numbers, triangular fuzzy Numbers, etc., to evaluate the reliability of equipment, and obtained the main reasons for equipment failures [3-5].Chen Tingting made it difficult to express the occurrence probability of various bottom events through certain values, but mainly used statistical data and approximate data in related fields or relied on expert judgment, which led to certain uncertainties in these probability values, including fuzziness and grey. Therefore, the probability of occurrence of top events simply based on this probability has no practical value, and the fuzziness and grayness of the system should be fully considered [6].

Based on the comprehensive analysis, the bottom events with higher fuzzy importance and higher frequency appear in the minimum cut set with higher correlation with top events, so as to provide a
more comprehensive and intuitive reference for the optimization design of key components and the establishment of preventive measures for the failure of ballast cleaning device.

2. Working principle of ballast cleaning machine and its device

According to the development requirements, the overall structure of railway turnout ballast cleaning machine is determined as shown in Figure 1, including ballast cleaning device, slewing and lifting device, transverse moving device, etc. Each device follows the principle of modular design, easy to disassemble and assemble.

![Figure 1. Structure diagram of switch ballast cleaning machine.](image)

Ballast cleaning mechanism of turnout ballast cleaning machine and side cut CQS - 300 type sieve machine work like clear frantic jumble of institutions, in the case of not dismantle section of track, the chain drive to cut from the bottom of the pillow, and the difference is this paper's frantic jumble of switch machine design with the method of intermittent from between two sleeper cut into the bottom of the pillow, greatly reduce the length of the ballast chain of this kind of design, more suitable for short distance of ballast cleaning, the early stage of the research design's frantic jumble of single drive mechanism diagram as shown in figure 4, from the frantic jumble chain, sprocket, knives, plate, etc.

![Figure 2. Schematic diagram of ballast cleaning mechanism.](image)

3. Qualitative and quantitative analysis of fuzzy fault tree of ballast cleaning mechanism

3.1 Qualitative analysis of fuzzy fault tree of ballast cleaning mechanism

The qualitative analysis of fault tree is to find out why top events occur, to work out a solution according to the simple and intuitive fault tree, and to find out the minimum cut set. The most don't want to happen in ballast cleaning system events for the frantic jumble device does not work, will clear the frantic jumble device does not work for fault tree top event T, the structural failure of ballast cleaning device is caused by the failure of ballast cleaning chain A (including raking claw fault Ab, Aa, chain sprockets Ac), shaft failure B, support system failure fault D, C, motor speed reducer failure cause, E for intermediate events, the end of each event in the ballast cleaning device improved FMEA forms are analyzed in detail, through the top and bottom events connected logic goalkeeper,
build up the fault tree as shown in figure 5, figure\textcircled{1} in the gate of logic or, Indicates that an output event occurs when any input event occurs.

\[
T = M_1 + M_2 + M_3 + X_8 + X_9 = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9
\]

\[\text{(1)}\]

Table 1. Events and code of ballast cleaning device Fault tree.

| Code name | The name of the event | Code name | The name of the event |
|-----------|----------------------|-----------|----------------------|
| T         | The ballast cleaning device does not work properly | X4        | Sprocket spindle has low stiffness |
| M1        | Ballast chain failure | X5        | Main sprocket shaft broken |
| M2        | Shaft failure        | X6        | Tool post fracture    |
| M3        | Accessory failure    | X7        | Bearing failure       |
| X1        | Rake jaw fracture    | X8        | Motor fault           |
| X2        | The chain failure    | X9        | Reducer failure       |
| X3        | Sprocket failure     |           |                      |

According to formula (3-20), the minimum cut set of the fault tree is \{X1\}, \{X2\}, \{X3\}, \{X4\}, \{X5\}, \{X6\}, \{X7\}, \{X8\}, \{X9\}. There is no redundancy in the fault tree of ballast cleaning device. Each bottom event will lead to the occurrence of top event.

3.2 Fuzzy fault tree of ballast cleaning mechanism

The purpose of traditional fault tree quantitative analysis is to calculate the probability of top events and the probability importance of bottom events to top events by calculating the failure probability of bottom events. Since the turnout ballast leaner designed in this paper belongs to the research and development stage, the fault data of railway sieve cleaner is very deficient, and the accurate value of bottom event probability cannot be obtained, so this section adopts the positive based on expert scoring method \(\tilde{p}_{(x)}\) represents the fuzzy probability of the bottom event [7]. By replacing the precise value probability with the normal fuzzy number probability, the result is more consistent with the objective fact. The membership function of the normal fuzzy number is:

\[
\text{...}
\]
\[ \tilde{P}(x) = e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]  

(2)

Type: \( \mu \) central value of \( \tilde{P}(x) \), \( \sigma \) for the deviation degree of \( \tilde{P}(x) \).

The normal probability distribution diagram is shown in Figure 6.

![Normal probability distribution](image)

**Figure 4.** Normal probability distribution.

### 3.2.1 Normal fuzzy Numbers of bottom events and top events

The invited three experts team to clear the frantic jumble device fault tree bottom event probability rate, assume that any failure event failure probability between 0.001 ~ 0.004, each expert to the probability of bottom events score for \( X_k \), fuzzy number is used to describe the failure probability of occurrence of events, The mean of the fuzzy probability is \( \mu \), the variance is \( \sigma \), calculation formula as shown in formula (2), (3), on the basis of bottom events fuzzy probability in table 2.

\[
\begin{align*}
\mu &= E(X_k) = (X_{k1} + X_{k2} + \cdots + X_{kn}) / n \\
\sigma^2 &= D(X_k) = [(X_{k1} - \mu)^2 + (X_{k2} - \mu)^2 + \cdots + (X_{kn} - \mu)^2] / n
\end{align*}
\]  

(3)  

(4)

| code | event                                      | Experts 1 | Experts 2 | Experts 3 | Normal fuzzy number                      |
|------|--------------------------------------------|-----------|-----------|-----------|-----------------------------------------|
| X1   | Rake jaw fracture                          | 0.0023    | 0.0034    | 0.0031    | (0.00293, 2.16×10^{-6})                 |
| X2   | The chain failure                          | 0.0025    | 0.0027    | 0.0028    | (0.00267, 1.56×10^{-7})                 |
| X3   | Sprocket failure                           | 0.0021    | 0.0024    | 0.0025    | (0.003, 4.7×10^{-6})                    |
| X4   | Sprocket shaft deformations                | 0.0033    | 0.0029    | 0.0022    | (0.0028, 2.07×10^{-6})                 |
| X5   | Sprocket shaft broken                      | 0.0018    | 0.0019    | 0.0017    | (0.0018, 6.7×10^{-8})                  |
| X6   | Tool post fracture                         | 0.0021    | 0.0016    | 0.0019    | (0.00187, 4.22×10^{-7})                |
| X7   | Bearing failure                            | 0.0022    | 0.0027    | 0.0029    | (0.0026, 1.43×10^{-6})                 |
| X8   | Motor fault                                | 0.0022    | 0.0017    | 0.0021    | (0.002, 4.67×10^{-7})                  |
| X9   | Reducer failure                            | 0.0021    | 0.0018    | 0.0016    | (0.00183, 4.22×10^{-7})                |

**Table 2.** Fuzzy probability evaluation table of events at the bottom.
3.2.2 Calculate the occurrence probability of intermediate events and top events

According to the fault tree algorithm [8], the fault tree of ballast cleaning device is calculated, and the Boolean operation formulas for intermediate events and top events are obtained as follows:

\[
\tilde{P}(T) = 1 - \left[ 1 - \tilde{P}(M_1) \right] \left[ 1 - \tilde{P}(M_2) \right] \left[ 1 - \tilde{P}(M_3) \right] \left[ 1 - \tilde{P}(X_9) \right]
\]

\[
\tilde{P}(M_1) = \left[ 1 - \tilde{P}(X_4) \right] \left[ 1 - \tilde{P}(X_2) \right] \left[ 1 - \tilde{P}(X_8) \right]
\]

\[
\tilde{P}(M_2) = 1 - \left[ 1 - \tilde{P}(X_4) \right] \left[ 1 - \tilde{P}(X_2) \right]
\]

\[
\tilde{P}(M_3) = 1 - \left[ 1 - \tilde{P}(X_6) \right] \left[ 1 - \tilde{P}(X_7) \right]
\]

The product of normal fuzzy Numbers is approximately normal fuzzy Numbers, and the membership function of the product of normal fuzzy Numbers is:

\[
\prod_{j=1}^{n} \tilde{P}(x_j) \approx e^{-\left( -\sum_{j=1}^{n} \mu_j \times \sigma_j \right)}
\]

The occurrence probability of top event and intermediate event can be obtained through fuzzy Boolean operation, as shown in Table 3.

| Intermediate events and top events | Normal fuzzy number |
|-----------------------------------|---------------------|
| \(\tilde{P}(M_1)\)               | (0.00637, 0.000655²) |
| \(\tilde{P}(M_2)\)               | (0.0041, 0.000432²) |
| \(\tilde{P}(M_3)\)               | (0.00398, 0.00046²) |
| \(\tilde{P}(T)\)                 | (0.00916, 0.000251²) |

3.2.3 Calculation of probability of occurrence of top event after removing bottom event

After removing the base event, the occurrence probability of the corresponding intermediate event will also change. To obtain the occurrence probability of the top event, the occurrence probability of the changed intermediate event must be obtained first. Taking the calculation of intermediate event \(M_1\) and top event after removing the base event \(X_1\) as an example, the calculation process is given as follows.

If you take away the base event \(X_1\), you solve \(\tilde{P}(M_1)\)

\[
\sum_{j=1}^{n} \left( \sigma_i \prod_{j=1, j \neq i}^{n} \mu_j \right) = \sigma_2 (1 - \mu_3) \sigma_3 (1 - \mu_2)
\]

\[
= \sqrt{1.56 \times 10^{-7}} \times 0.997 + \sqrt{4.7 \times 10^{-6}} \times 0.99733 = 0.00215
\]

To solve the \(\tilde{P}(T_1)\)

\[
\tilde{P}(T_1) = 1 - \left[ 1 - \tilde{P}(X_1) \right] \left[ 1 - \tilde{P}(X_2) \right] \left[ 1 - \tilde{P}(M_2) \right] \left[ 1 - \tilde{P}(M_3) \right] \left[ 1 - \tilde{P}(X_8) \right] \left[ 1 - \tilde{P}(X_9) \right]
\]

\[
\tilde{P}(T_1) = 0.0184
\]

Similarly, the occurrence probability of the remaining top events after removing the bottom events can be obtained, as shown in Table 4.
Table 4. Occurrence probability of top events after removing bottom events.

| \( \tilde{P}(T_j) \) | probability of occurrence |
|----------------|---------------------------|
| 1              | (0.0184, 0.00376\(^2\))  |
| 2              | (0.0186, 0.0042\(^2\))   |
| 3              | (0.0183, 0.00337\(^2\))  |
| 4              | (0.0185, 0.00398\(^2\))  |
| 5              | (0.0195, 0.00381\(^2\))  |
| 6              | (0.0193, 0.00372\(^2\))  |
| 7              | (0.0187, 0.00223\(^2\))  |
| 8              | (0.0190, 0.00374\(^2\))  |
| 9              | (0.0194, 0.00368\(^2\))  |

3.2.4 The importance of each event

Suppose there are two normal fuzzy Numbers A and B, and the distance between them is determined by Equation (3-25):

\[
\text{When the probability importance degree of bottom event of ballast cleaning device is desired, the distance between top event } \tilde{P}(T) \text{ and top event of removing a bottom event } \tilde{P}(T_j) \text{ can be obtained through Equation (3-25) to represent. The greater the distance, the more important the bottom event is to the whole fault tree.}
\]

The calculation results of the distance between \( \tilde{P}(T) \) and \( \tilde{P}(T_j) \) are shown in Table 5. It can be seen from the table that, the first two in the importance ranking of the event at the bottom of the fault tree of the ballast cleaning device are the fracture failure of the rake claw and the sprocket wheel. In order to ensure the high reliability of the key parts, the rake claw and the sprocket wheel should be optimized for design.

Table 5. Distance between \( \tilde{P}(T) \) and \( \tilde{P}(T_j) \).

| \( d_2^2(\tilde{P}(T), \tilde{P}(T_j)) \) | result (\( \times 10^4 \)) |
|----------------|--------------------------|
| 1              | 13.03                    |
| 2              | 11.05                    |
| 3              | 13.32                    |
| 4              | 11.97                    |
| 5              | 4.45                     |
| 6              | 4.71                     |
| 7              | 9.07                     |
| 8              | 5.16                     |
| 9              | 4.29                     |

4. FMEA analysis of ballast cleaning device

According to the different product life cycle, FMEA is divided into DFMEA (design stage) and PFMEA (process and production test stage). DFMEA is mainly classified according to the functions realized by the product. The turnout ballast-cleaning machine involved in this paper is in the state of design and development, so it belongs to the category of DFMEA [9]. The purpose of DFMEA is to find out the possible failure modes of the product in the design stage, and to provide the corresponding failure compensation measures through the in-depth analysis of various failure modes so as to reduce the fault incidence and improve the reliability of the product in the use stage.

According to the analysis in the second section, FMEA is carried out on the rake claw and chain drive of ballast cleaning device, and FMEA table is developed, as shown in the table.
| code | Failure mode                  | The cause of the problem                  | Fault impact                                      | Improved compensation measures                  |
|------|------------------------------|------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| Aa1  | Rake plate fracture         | Small thickness and insufficient strength. | Ballast cleaning efficiency slows down            | Increase the thickness                          |
| Aa2  | The rake plate is too       | Ballast impact is large                   | The force becomes larger, affecting the efficiency of ballast cleaning | Reinforce the rake plate at the right position  |
|      | deformed                    |                                          |                                                  |                                                  |
| Aa3  | The teeth of the rake are   | The structural design is not reasonable   | The rising cost of                               | Wear - resistant alloy steel and appropriate heat treatment |
|      | badly worn                  |                                          |                                                  | Increase the diameter of the cylinder pin or replace it with another fixed method |
| Aa4  | Cylinder pin fall off       | The cylindrical pin size is too small and the welding is not firm | Rake tooth drop                                  | Increase the diameter of the cylinder pin or replace it with another fixed method |
| Ab1  | The chain rupture           | Fatigue wear, rake claw weight is too heavy | Failure of traction function                     | High strength alloy chains are used for heat treatment |
| Ab2  | Chain stuck                 | The structural design is not reasonable   | It doesn't run smoothly or even work             | Design protection                               |
| Ab3  | The chain to take off the   | Tension is insufficient                   | Affect the efficiency of ballast cleaning work   | Replace the hydraulic tension                   |
|      | chain                        |                                          |                                                  |                                                  |
| Ab4  | Excessive deformation of    | Improper chain selection or excessive tension | The chain failure                               | Change the chain type or tighten the chain appropriately |
|      | chain pin                   |                                          |                                                  |                                                  |
| Ac1  | Failure mode                | The cause of the problem                  | Drive failure                                    | Improve the sprocket heat treatment process     |
| Ac2  | Rake plate fracture         | Small thickness and insufficient strength. | Vibration occurs, affecting the running stability | Check the lubrication sprocket periodically and replace the sprocket regularly                  |
|      |                              |                                          |                                                  |                                                  |
| Ac3  | The rake plate is too       | Ballast impact is large                   | Aggravate sprocket wear, cause chain to run unsteadily | Strict quality control and proper installation of sprockets |
|      | deformed                    |                                          |                                                  |                                                  |

The improved ballast cleaning device is shown in Figure 10.
1- Driving sprocket shaft assembly;2- Transmission frame;3- Intermediate sprocket shaft assembly;4 tensioning device;5- Driven sprocket shaft assembly;6 - the frantic jumble chain

Figure 5. Schematic diagram of improved ballast cleaning mechanism.

5. Conclusion
This article through the establishment of frantic jumble device fault tree, and has carried on the qualitative analysis, the minimum cut sets of the clear the frantic jumble device, in the traditional fault tree on the basis of introducing the theory of normal fuzzy Numbers, using the normal fuzzy number theory combined with expert evaluation method, the distance of two fuzzy Numbers represent important degree of the bottom to the top events, got the key components of clear frantic jumble device for raking claw and sprocket. The FMEA method is also used to analyze the key parts of the ballast cleaning device, and corresponding optimization design and compensation measures are proposed according to the specific failure reasons.

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