System reliability analysis of forage crushing machine based on fuzzy FMECA

X Y Zhai¹, Z P Zhai¹, Y Z Lan¹, Y M Wu², H Y Cheng¹ and C C Zhang³

¹ College of Mechanical Engineering, Inner Mongolia University of Technology, Hohhot, 010051, China
² Hohhot Branch of Chinese Academy of Agricultural Mechanization Sciences, Hohhot, 010020, China
³ School of Economics and Management, Inner Mongolia University of Technology, Hohhot, 010051, China

E-mail: ngdzghzp@imut.edu.cn

Abstract. This paper aims to address the problems of high failure rate, poor reliability, and incomplete failure data associated with forage crushing machines. First, the failure mode effects and criticality analysis (FMECA) is combined with the fuzzy theory to transform the influencing factors on failure modes into fuzzy variables. Then, the analytic hierarchy process (AHP) is used to determine the weight of each influencing factor, and a comprehensive criticality degree is calculated for each failure mode to determine the key component posing the greatest criticality of disrupting the operation of the equipment. The results of the analysis show that fuzzy FMECA can be used to rank the comprehensive criticality degree of each failure mode. Furthermore, the results are consistent with the criticality ranking of failure modes obtained under actual operating conditions and can therefore be to determine the most critical failure mode and the key component. Fuzzy FMECA also provides valuable reference data for improving the design and system reliability and to effectively reduce the failure rate of forage crushing machines.

1. Introduction

Forage crushing machines are used to process crop straw, vines, stems, or thick grass after they are cut to produce softer forage materials, which can increase livestock feeding rates by improving digestibility and can also facilitate long-term storage. During the operation of the forage crushing machine, forage is crushed between high-speed blades and a serrated plate, which is on the inner wall of the machine. Then, the crushed forage is transported out of the machine by a forage-throwing mechanism. At present, failure rates of forage crushing machines are high. Therefore, low reliability has become the main problem during the crushing operation. The average mean time between failures (MTBF) of machines is typically less than two-thirds of those of similar products in the international advanced enterprise, moreover, the number of machines that meet international standards is less than 5%, which makes it difficult to meet the needs of users. [1]

Reliability is not typically considered in the design of forage crushing machines. therefore, accurately analyzing the criticality of certain failure modes of forage crushing machine is necessary to provide a basis for improving reliability. Failure mode effects and criticality analysis (FMECA) is a method used to analyze potential failure modes and their impact on the function of the system.
The failure modes are classified according to criticality degree and probability of incidence, then preventive measures for improving system reliability are proposed [2]. Human factors greatly affect FMECA, therefore, the complexity and fuzzy uncertainty of failure modes cannot be taken into account. Moreover, accurate quantitative analysis on the criticality of each failure mode is impossible owing to a lack of statistical data and experience in analyzing related products.

To solve the above problems, many scholars have combined FMECA with fuzzy theory. Hu et al. [3] proposed a fuzzy FMECA to improve the failure diagnosis of hydraulic systems, which was shown to improve the reliability of hydraulic equipment. Through theoretical analysis and illustration with a hydraulic system, Li et al. [4] showed that more comprehensive results that are closer to reality are achieved when FMECA is combined with fuzzy theory. Su et al. [5] showed that cloud model-based fuzzy FMECA can be used to transform quantized values into exact values by incorporating ambiguity and randomness, resulting in better consistency. Balaraju et al. [6] used fuzzy FMEA to obtain the highest fuzzy criticality priority number (RPN) to reduce the probability of the second incidence of equipment failure. Zhu et al. [7] applied a fuzzy set theory to quantitatively analyze and diagnose failures in urban rail transit systems and to improve operational efficiency. By comparing results obtained using FMEA with those of fuzzy FMEA, Renjith et al. [8] demonstrated that difficulties with prioritizing the RPN of complex systems, such as liquified natural gas storage tanks, can be addressed with fuzzy FMECA. Lee et al. [9] proposed a control method based on fuzzy theory and obtained accurate evaluation results using the fuzzy expert system to conduct fuzzy synthesis. Selvakumar et al. [10] presented a methodology to calculate the RPN and identified the key component of a centrifugal pump to improve its reliability. Pei et al. [11] applied fuzzy FMECA to a hydraulic system and used comprehensive evaluation to rank the criticality of each failure mode of hydraulic system components, which can be used to improve reliability and to schedule timely maintenance. Kim et al. [12] applied the fuzzy analytic hierarchy process (AHP) to determine reasonable weights for the criticality evaluation of raw materials, which resulted in more accurate and reliable results. Zhou et al. [13] used fuzzy theory and grey theory to assign weights to influencing factors, which can improve the accuracy of failure prediction.

To accurately analyze the criticality of failure modes of the forage crushing machine, and to reduce the influence of human factors and incomplete failure data on the evaluation results, this paper adopts fuzzy FMECA to analyze system reliability. At the same time, AHP is used to determine reasonable weights for each influencing factor. The results are close to actual operating conditions and provide a theoretical basis for accurate failure mode analysis.

The rest of this paper is organized as follows. Section 1 introduces the fuzzy FMECA model. Section 2 presents an example of a practical application of the system reliability analysis based on fuzzy FMECA for the forage crushing machine. The main conclusions of the study are summarized in Section 3.

2. Theory of fuzzy FMECA

Fuzzy FMECA is the combination of FMECA and fuzzy theory, which are combined to solve the shortcomings of FMECA, such as human factors and incomplete failure data, that often lead to inaccurate criticality analyses. A flowchart of the specific analysis process is shown in Figure 1 [14].

![Figure 1. Flowchart of fuzzy FMECA process.](image-url)
2.1. Establishing the Influencing Factor Set
The influencing factor set is composed of the factors determining the criticality of the evaluated object,

$$U = \{u_1, u_2, \ldots, u_i, \ldots, u_n\}$$  \hspace{1cm} (1)

where, $U$ represents the influencing factor set; $u_i$ represents the influencing factor which ranked as $i$, $(i=1,2,3,\ldots,n)$; $n$ is the total number of influencing factors.

2.2. Establishing the Evaluation Set
The evaluation set represents the set composed of the criticality level for the evaluated object,

$$V = \{v_1, v_2, \ldots, v_j, \ldots, v_m\}$$  \hspace{1cm} (2)

where, $V$ represents the evaluation set; $v_j$ represents the criticality level ranked by $j(j=1,2,3,\ldots,m)$; $m$ is the total number of criticality levels.

2.3. Determining the Fuzzy Evaluation Matrix of Influencing Factors
To establish the fuzzy evaluation matrix, membership set $R^k_i$ of the influencing factors of the failure modes $k$ must first be determined relative to $v_j$. It is assumed that the evaluation team is made up of $h$ experts who provide scores, and each expert can only provide one score for each influencing factor of each failure mode according to $V$. If the number of experts who believe that $u_i$ is affiliated with $v_j$ is $h_{ij}$ out of $h$, the evaluation set of $u_i$ is

$$R^k_i = \left\{ \frac{h_{i1}}{h}, \frac{h_{i2}}{h}, \ldots, \frac{h_{im}}{h} \right\} = \left\{ r^k_{i1}, r^k_{i2}, \ldots, r^k_{im} \right\}$$  \hspace{1cm} (3)

Therefore, the fuzzy evaluation matrix composed of the evaluation set of failure modes $k$ is

$$R^k = \begin{bmatrix} R^k_1 & R^k_2 & \cdots & R^k_n \end{bmatrix} = \begin{bmatrix} r^k_{11} & r^k_{12} & \cdots & r^k_{1m} \\ r^k_{21} & r^k_{22} & \cdots & r^k_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r^k_{n1} & r^k_{n2} & \cdots & r^k_{nm} \end{bmatrix}$$  \hspace{1cm} (4)

Moreover, $\sum_{j=1}^{m} r^k_{ji} = 1$, that is, the evaluation set of each influencing factor satisfies the principle of normalization.

2.4. Determining the Weight Set of Influencing Factors
In fuzzy FMECA, one of the most important components is the weight of each influencing factor of each failure mode. In criticality analysis, the importance of various influencing factors will be quite different. Therefore, it is necessary to determine the weight of each influencing factor, which makes up the weight set.

Methods to determine the weight of influencing factors include expert evaluation, investigation analysis, and AHP. The first two methods are highly influenced by human factors and easily produce large deviations, whereas AHP can eliminate the influence of human factors and ensure accurate results.

The specific steps of AHP are as follows:

1) Determine the relative importance of influencing factors $u_i$ to influencing factors $u_j$, represented by $c_{ij}$. Construct judgment matrix $C$, then calculate the maximum eigenvalue $\lambda_{\text{max}}$ of judgment matrix $C$. 

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix}$$

$$\lambda_{\text{max}} = \text{max} \{ \lambda \}$$

where $\lambda$ is an eigenvalue.
Specific values of $c_{ij}$ are presented in Table 1, $c_{ii}=1$ and $c_{ij}=1/c_{ji}$.

**Table 1.** Importance scale of judgment matrix and its meaning [15].

| Meaning                                           | $c_{ij}$ | Note                          |
|---------------------------------------------------|----------|-------------------------------|
| $u_i$ is as important as $u_j$                     | 1        |                               |
| $u_i$ is slightly more important than $u_j$       | 3        |                               |
| $u_i$ is obviously more important than $u_j$      | 5        |                               |
| $u_i$ is more important than $u_j$                | 7        |                               |
| $u_i$ is much more important than $u_j$           | 9        |                               |
| the relative importance of $u_i$ and $u_j$ is     | 2,4,6,8  | the median between two grades |
| between the above grades                          |          |                               |

2) Calculate the consistency ratio $R_c$, which is used to assess the consistency of the matrix, using the following formula [16]:

$$I_c = \frac{\lambda_{\text{max}} - n}{n - 1}$$  \hspace{1cm} (6)

$$R_c = \frac{I_c}{I_s}$$  \hspace{1cm} (7)

where $I_c$ is the consistency index of the judgment matrix and $I_s$ is the mean random consistency index of the judgment matrix. For matrices of the order 1~13, specific values of $I_s$ are listed in Table 2. Finally, the consistency of the judgment matrix $C$ is assessed. When $R_c < 0.1$, judgment matrix $C$ is consistent, and the weight distribution is reasonable. Otherwise, judgment matrix $C$ must be modified appropriately.

**Table 2.** The different values of $I_s$ in the matrix of order 1~13 [15].

| $n$ | $I_s$ | $n$ | $I_s$ |
|-----|-------|-----|-------|
| 1   | 0     | 8   | 1.14  |
| 2   | 0     | 9   | 1.45  |
| 3   | 0.58  | 10  | 1.49  |
| 4   | 0.90  | 11  | 1.52  |
| 5   | 1.12  | 12  | 1.54  |
| 6   | 1.24  | 13  | 1.56  |
| 7   | 1.32  |     |       |

3) Calculate the weight vector of the influencing factors. Generally, the arithmetic mean method (summation method) is used to calculate the relative weight of influencing factors. In judgment matrix $C$, each column approximately reflects the weight distribution of the influencing factors, therefore, the arithmetic mean values of all column vectors can be used to approximately calculate the weight values. The specific formula is [17]

$$I_j = \frac{1}{n} \sum_{i=1}^{n} \frac{c_{ij}}{\sum_{k=1}^{n} c_{kj}}$$  \hspace{1cm} (8)

The weight set is
\[ L = \{l_1, l_2, l_3, \ldots, l_i, \ldots, l_n\} \]  \hspace{1cm} (9)

where \(0<l_i<1, i \in [1, n]\), and \(\sum_{i=1}^{n} l_i = 1\).

2.5. First Level of Fuzzy Comprehensive Evaluation

The result of multiplying the weight set of influencing factors and the evaluation matrix is regarded as the first level of fuzzy comprehensive evaluation vector \(B^k\), which reflects the membership degree of failure mode \(k\) relative to criticality level,

\[
B^k = (l_1, l_2, \ldots, l_n) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} = (b_1, b_2, \ldots, b_m) \]  \hspace{1cm} (10)

Since \(B^k\) is the comprehensive evaluation results of all influencing factors, according to the principle of maximum membership degree, the corresponding criticality level of \(b_i\), which is the largest value in \(B^k\) is selected as the comprehensive evaluation result.

To assess and compare the criticality degree of each failure mode more intuitively and accurately, and to determine the failure mode which poses the greatest criticality, \(B^k\) can also be weighted and averaged to obtain \(D^k\),

\[
D^k = B^k V^T
\]  \hspace{1cm} (11)

where \(D^k\) represents the comprehensive criticality degree.

2.6. Second level of Fuzzy Comprehensive Evaluation

The first level fuzzy evaluation evaluates the lower system, and the second level fuzzy evaluation is needed to evaluate the upper system. The influencing factors set \(U\) of the second level of fuzzy comprehensive evaluation are all failure modes,

\[ U = \{k_1, k_2, k_3, \ldots, k_i, \ldots, k_n\} \]  \hspace{1cm} (12)

The evaluation set remains unchanged and the weight set can be calculated using AHP. Then, the comprehensive criticality degree \(D\) is calculated. Finally, the criticality degree is ranked to determine the key component of the system.

3. System reliability analysis of forage crushing machine based on fuzzy FMECA

The forage crushing machine is mainly composed of a power and power transmission section, shell, and rotor. To improve the reliability of the forage crushing machine and to reduce the failure rate of a key component, fuzzy FMECA can be adopted to quantitatively analyze the criticality degree of failure modes of a forage crushing machine. The 9R-40 forage crushing machine is taken as an example in this paper.

3.1. System reliability analysis of forage crushing machine based on FMECA

The failure data, including failure modes, causes of failure, and measures to address failure modes of the forage crushing machine are provided by the agricultural machinery enterprises. From the perspective of the incidence of failure (O), degree of severity (S) and difficulty of detection (D), each failure mode was evaluated and scored by 10 engineers and technicians. The RPN value was then obtained by multiplying scores of the three influencing factors. Finally, an FMECA table of forage crushing machines was established, as shown in Table 3.
Table 3. FMECA table for forage crushing machine.

| Location of failure                  | Code | Failure mode            | Cause of failure                                      | Effect of failure                      | Measure used to deal with failures                  | O  | S  | D  | RPN |
|-------------------------------------|------|-------------------------|-------------------------------------------------------|----------------------------------------|----------------------------------------------------|-----|----|----|-----|
| Power and power transmission section| 1    | Weak operation of machine | Motor is out of phase operation or failure             | Machine does not work properly         | Inspect and repair motors, wires, etc.             | 1   | 3  | 2  | 6   |
|                                     | 2    | V belts easily fall off  | Tension of each V belt is different or too loose      | Machine does not work properly         | Replace the same length or tighten V belts         | 2   | 3  | 1  | 6   |
|                                     | 3    | Breakage of V belts     | Insufficient fatigue strength of V belts              | Machine does not work properly         | Replace the V belts                                | 2   | 3  | 2  | 12  |
| Shell                              | 4    | Severe vibration of machine | The unbalance of rotor                               | Noise of machine increase or the machine fails | Balance rotor                                     | 3   | 4  | 2  | 24  |
|                                     | 5    | Material jam            | Too much input                                        | Machine does not work properly         | Stop machine and troubleshoot                      | 3   | 3  | 1  | 9   |
|                                     | 6    | Machine makes unusual noise | Joints of machine are loose                         | Noise of machine increases             | Stop machine and troubleshoot                      | 2   | 2  | 2  | 8   |
| Rotor                              | 7    | Wear of the blades      | Blades are dulled                                    | Crushing effect of machine is poor     | Replace blades                                     | 4   | 3  | 2  | 24  |
|                                     | 8    | Cracking of blades      | Insufficient fatigue strength of blades              | Machine fails                          | Replace blades                                     | 2   | 4  | 3  | 24  |
|                                     | 9    | Excessive bending of rotor shaft | Insufficient stiffness of rotor shaft                | Crushing effect of machine is affected | Replace rotor shaft                                | 1   | 2  | 3  | 6   |

Table 3 shows that the reliability analysis of the forage crushing machine based on FMECA has a large subjectivity problem since the failure data are incomplete. This results in six failure modes with RPN values of 24 or 6 and the criticality degree of these failure modes cannot be determined, suggesting the FMECA results have low accuracy.

3.2. System reliability analysis of forage crushing machine based on fuzzy FMECA

3.2.1. Establishing the Influencing Factor Set

Three types of influencing factors are related to the criticality degree of the failure mode of the forage crushing machine: incidence of failure, degree of severity, and difficulty of detection. Therefore, the set of influencing factors is $U = \{O, S, D\}$.

3.2.2. Establishing the Evaluation Set

Generally, the criticality level of failure modes of the forage crushing machine is 4 [18], so the evaluation set is $V = \{1, 2, 3, 4\}$. The criticality level of influencing factors is presented in Table 4.

Table 4. Criticality level of the influencing factors.

| Influencing factors | Level |
|---------------------|-------|
|                     | 1     | 2     | 3     | 4     |
| $O$                 | Rarely| Once in a while | Sometimes | Often |
| $S$                 | No effect | Mild effect | Moderate effect | Fatal effect |
| $D$                 | Easy | Not easy | More difficult | Unable |

3.2.3. Determining the Fuzzy Evaluation Matrix of Influencing Factors
The seventh failure mode, namely wear of the blades, occurs frequently and is presented as an example. The fuzzy evaluation matrix of influencing factors was determined. The results evaluated by 10 engineers and technicians were substituted into Equation (3) to determine the incidence of failure \( O \), degree of severity \( S \), and difficulty of detection \( D \), which were calculated as \( R_7^1 = \{0,0.1,0.1,0.8\} \), \( R_7^2 = \{0,0.3,0.7,0\} \), and \( R_7^3 = \{0.1,0.7,0.2,0\} \), respectively. Thus, the fuzzy evaluation matrix of the seventh failure mode is

\[
R^7 = \begin{bmatrix}
0 & 0.1 & 0.1 & 0.8 \\
0 & 0.3 & 0.7 & 0 \\
0.1 & 0.7 & 0.2 & 0
\end{bmatrix}
\] (13)

3.2.4. Determining the Weight Set of Influencing Factors

The relative importance of three influencing factors of the seventh failure mode was evaluated can be scored by 10 related engineers and technicians, as shown in Table 1. Substituting the results into Equation (5), we obtain the judgment matrix of influencing factors of the forage crushing machine,

\[
C^7 = \begin{bmatrix}
1 & 1/3 & 2 \\
3 & 1 & 7 \\
1/2 & 1/7 & 1
\end{bmatrix}
\] (14)

From judgment matrix \( C^7 \), the maximum eigenvalue \( \lambda_{\text{max}} = 3.0026 \) was obtained, then the consistency index \( I_c = 0.0013 \) was obtained by substituting \( n = 3 \) into Equation (6). According to Table 2, the average random consistency index of the judgment matrix \( I_s \) is 0.58. Then, the consistency ratio of judgment matrix \( R_c = 0.0023 \) was calculated using Equation (7), and \( R_c = 0.0023 < 0.1 \). Therefore, the consistency of judgment matrix \( C^7 \) of the seventh failure mode meets the requirements, indicating that the weight distribution is reasonable.

By substituting the judgment matrix (14) into Equation (8), the weights of the three influencing factors of the seventh failure mode are \( l_1 = 0.216 \), \( l_2 = 0.618 \), and \( l_3 = 0.103 \). Then, the weight set is

\[
L = \{0.216,0.681,0.103\}
\] (15)

3.2.5. First Level of Fuzzy Comprehensive Evaluation on Forage Crushing Machine

The product of weight set (15) and fuzzy judgment matrix (13) were taken as the results of the first level fuzzy comprehensive evaluation of the seventh failure mode,

\[
B^7 = LR^7 = \{0.0103,0.2980,0.5189,0.1728\}
\]

That is, membership degrees of the criticality of the seventh failure mode relative to \( V = \{1,2,3,4\} \) are 0.0103, 0.2980, 0.5189 and 0.1728, respectively. According to the principle of maximum membership, the criticality level of the seventh failure mode is 3. To analyze the criticality of the seventh failure mode more intuitively, the comprehensive criticality degree was calculated using Equation (11), as follows:

\[
D^7 = B^7 V^T = \{0.0103,0.2980,0.5189,0.1728\} \cdot \{1,2,3,4\}^T = 2.8542
\]

In the same way, the comprehensive criticality degree of other failure modes in the system were calculated,

First failure mode:

\[
B^1 = LR^1 = \{0.5326,0.3139,0.1453,0.0082\}, \; D^1 = 1.6291
\]

Second failure mode:

\[
B^2 = LR^2 = \{0.5417,0.3120,0.1439,0.0024\}, \; D^2 = 1.6070
\]

Third failure mode:

\[
B^3 = LR^3 = \{0.3329,0.1929,0.4201,0.0641\}, \; D^3 = 2.2254
\]
Fourth failure mode:
\[ B^4 = LR^4 = \{0.0036, 0.2321, 0.6912, 0.0729\}, \quad D^4 = 2.8332 \]

Fifth failure mode:
\[ B^5 = LR^5 = \{0.3153, 0.4315, 0.2326, 0.0204\}, \quad D^5 = 1.9571 \]

Sixth failure mode:
\[ B^6 = LR^6 = \{0.3517, 0.4256, 0.2052, 0.0175\}, \quad D^6 = 1.8885 \]

Eighth failure mode:
\[ B^8 = LR^8 = \{0.0566, 0.1326, 0.7192, 0.0915\}, \quad D^8 = 2.8455 \]

Ninth failure mode:
\[ B^9 = LR^9 = \{0.5157, 0.3217, 0.1463, 0.0126\}, \quad D^9 = 1.6484 \]

From the above results, it can be seen that failure modes of the forage crushing machine can be ranked according to the comprehensive criticality degree, as follows: wear of blades > cracking of blades > severe vibration of machine > breaking of V belts > material jam > machine makes unusual noise > excessive bending of rotor shaft > weak operation of machine > V belts easily fall off. The failure modes of each component of the forage crushing machine can also be ranked according to the comprehensive criticality degree. For the power transmission: breaking of V belts > weak operation of machine > V belts easily fall off. For the shell: severe vibration > material jam > machine makes unusual noise. For the rotor: wear of the hammer > cracking of the hammer > excessive bending of rotor shaft. The comprehensive evaluation results presented above are consistent with the situation during the actual operation of the equipment.

3.2.6. Second Level Fuzzy Comprehensive Evaluation on Forage Crushing Machine

To quantitatively assess the comprehensive criticality degree of each component of the forage crushing machine, including a power and power transmission section, shell, and rotor, the second level fuzzy comprehensive evaluation was carried out using the results of the first level evaluation.

In this paper, the rotor is taken as an example. The comprehensive criticality degrees of each failure mode were calculated and sorted. The three types of failure mode of the rotor are the elements of the influencing factor set, that is, \( U = \{\text{seventh failure mode}, \text{eighth failure mode}, \text{ninth failure mode}\} \). The evaluation set is still \( V = \{1, 2, 3, 4\} \). The evaluation matrix of influencing factors is composed of the vectors of the first level fuzzy comprehensive evaluation of the seventh, eighth, and ninth failure modes,

\[
R_3 = \begin{bmatrix} B^7 & B^8 & B^9 \end{bmatrix}^T = \begin{bmatrix} 0.0103 & 0.2980 & 0.5189 & 0.1728 \\ 0.0566 & 0.1326 & 0.7192 & 0.0915 \\ 0.5157 & 0.3217 & 0.1463 & 0.0126 \end{bmatrix}
\]

Then, the weight of each influencing factor of the rotor was calculated using the AHP, and \( L_3 = \{0.465, 0.459, 0.076\} \). Finally, the result of the second level of the fuzzy comprehensive evaluation of the rotor was calculated,

\[ B_3 = L_3 R_3 = [0.0699, 0.2238, 0.5825, 0.1233], \quad D_3 = 2.7582 \]

Similarly, results of the second level fuzzy comprehensive evaluation for the power and power transmission and shell were calculated as

\[ B_1 = L_1 R_1 = [0.4403, 0.3943, 0.0847, 0.0807], \quad D_1 = 1.8058 \]
\[ B_2 = L_2 R_2 = [0.1448, 0.4193, 0.3621, 0.0727], \quad D_2 = 2.3605 \]

Based on the results for the second level fuzzy comprehensive evaluation of each component of the forage crushing machine, failure of the rotor is most harmful to the forage crushing machine, followed by the shell, and lastly, the power and power transmission section. Thus, the rotor is the key component of the forage crushing machine and also the main reason for the low reliability of the system.
4. Conclusion
This paper first presented fuzzy FMECA to transform the influencing factors on failure modes into fuzzy variables, and to rank each failure mode based on its comprehensive criticality degree. The results can then be used to accurately determine the most harmful failure mode based on the actual operating conditions of the forage crushing machine, even with insufficient failure data. Besides, the AHP was used to determine the weight of each influencing factor. The effect of human factors on the accuracy of the weight is eliminated as much as possible to help overcome the low accuracy of FMECA, which does not consider the relative weight of influencing factors. Finally, the fuzzy FMECA was used to conduct a multistage analysis of the criticality of failure modes of a forage crushing machine. We found that the key component affecting system reliability is the rotor, which has the highest comprehensive criticality degree and should be addressed to improve the reliability of forage crushing machines. This paper provides a useful reference for improving reliability and reducing the failure rate of forage crushing machines.

Acknowledgments
This research is supported by the Inner Mongolia Natural Science Foundation (No. 2018MS05059) and Inner Mongolia Autonomous Region Science and Technology Planning Project (2019).

References
[1] Li P T 2018 Study on failure rate model and selection optimization of rotary tillage tool in dryland soil Doctor Dissertation 144
[2] Xiao L L 2011 Study on reliability of horizontal screw centrifuge Master Dissertation 74
[3] Hu Q G and Shen X X 2017 Reliability analysis of amphibious vehicle hydraulic system based on fuzzy FMECA Machine tools and hydraulics 45 168-73
[4] Li H and Qiu C F 2012 Application of fuzzy FMECA method in reliability analysis of hydraulic system Hydraulically pneumatic and sealed 32 38-42
[5] Su H S, Wang D T and Su L 2019 Fuzzy FMECA risk evaluation and its applications in Chinese train control systems based on cloud model Journal of Intelligent & Fuzzy 37 1299-399
[6] Balaraju J, Govinda R M and Murthy C S 2019 Fuzzy-FMEA risk evaluation approach for LHD machine-A case study Journal of Sustainable Mining 18
[7] Zhu W, Li C Y, Xiao X Y and Xu W B 2015 Diagnosing urban rail transit vehicles with FMEA and fuzzy set Journal of Quality in Maintenance Engineering 21 332-45
[8] Renjith V R, Kalathil M J, Kumar P H and Madhavan D 2018 Fuzzy FMECA of LNG storage facility Journal of Loss Prevention in the process 56 537-47
[9] Lee Y S et al 2011 New FMECA methodology using structural importance and fuzzy theory IEEE Transactions on Power Systems 26 2364-7
[10] Selvakumar J and Natarajan K 2017 Reliability analysis of centrifugal pump through FMECA and FEM International Journal of Performability Engineering 13 119-28
[11] Pei C H, Liu X Y, Liu Z G, Zhang T and Li G L 2019 Fuzzy reliability analysis and optimization design of hydraulic system of bale carrier for tie arm device International Journal of Performability Engineering 15 416-30
[12] Kim J, Lee J, Kim B C and Kim J 2019 Raw material criticality assessment with weighted indicators: An application of fuzzy analytic hierarchy process Resources Policy 60
[13] Zhou Q and Thai V V 2016 Fuzzy and grey theories in failure mode and effect analysis for tanker equipment failure prediction Safety Science 83 74-9
[14] Dai G C, Wang X H, Zhang X and Wang L Z 2011 Electro-hydraulic servo valve FMECA based on fuzzy comprehensive evaluation Journal of Beijing University of Aeronautics and Astronautics 37 1575-8
[15] Saaty T L 1980 The Analytic Hierarchy Process (New York: McGraw-Hill)
[16] Li Y H and Yao W Z 2009 A method for hazard analysis of fault modes of railway freight cars Railway Science in China 30 103-8

[17] Deng X, Li J M, Zeng H J, Chen J Y and Zhao J F 2012 Analytic Hierarchy Process weight calculation method analysis and application research Practice and Understanding of Mathematics 42 93-100

[18] Hu W Z, He K, Qian J C, Geng D Y, Zhang G H and Lu X F 2018 Research on agricultural machinery FMECA method based on fuzzy comprehensive evaluation Journal of Agricultural Machinery S1 332-7