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Risk Assessment and Reliability Analysis of Oil Pump Unit Based on D-S Evidence Theory

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Abstract: Oil pumps are crucial equipment in pipeline transportation, and their safe and reliable operation is essential for the smooth and efficient operation of the oil station and associated pipelines. The failure of oil pumps can result in significant consequences, making it crucial to evaluate their safety for effective maintenance and reliable system prediction. Failure mode, effects, and criticality analysis (FMECA) is a quantitative fault analysis technique that assigns priority to fault modes using the *risk priority number* (*RPN*). However, the *RPN* may not accurately express uncertainty judgments of risk factors given by multiple experts. To address this limitation, this paper proposes a novel FMECA method based on the D-S evidence theory. The method involves using interval form to obtain risk factor evaluations from experts and data combination to obtain a multi-value representation of the *RPN* for each fault mode. The prioritization of fault modes is optimized using confidence and fidelity distribution to eliminate multiple modes of the same level. Finally, the normalization method is used to determine the risk degree ranking of oil pump units. Overall, the proposed method is an effective and practical approach for the risk evaluation and reliability analysis of oil pump units.

Keywords: FMECA; D-S evidence theory; oil pump; risk assessment; reliability analysis

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1. Introduction

With the rapid development of the pipeline industry, the use of pump units in pipeline transportation businesses has become increasingly prevalent. This has led to a higher demand for oil pump safety indexes. When an oil pump breaks down, it can lead to liquid leakage or shutdown and cause economic losses for pipeline transportation enterprises and even personal injury accidents [1]. According to our field research, in China's oil transfer stations, operating oil pump units have different equipment configurations resulting in various types and manufacturers that differ in quality and performance due to installation during different periods. The failure rate of each pump type varies between 5.6% and 20%, resulting in high failure rates for some equipment, which accounts for approximately 80% of the total annual maintenance costs. At present, the fault diagnosis of oil pump units during crude oil transportation mainly relies on the experience of maintenance personnel, which may not accurately identify the cause of accidents and their patterns for change [2]. Thus, conducting a safety risk analysis and assessment of oil pump units is of great significance for discovering hidden hazards and risks during oil storage and transportation processes for the safe operation of pipelines and oil transmission stations [3].

Failure mode, effects, and criticality analysis (FMECA) is a quantitative risk assessment method widely applied in various industries, including aviation [4], nuclear power [5], medicine [6], machinery manufacturing [7], offshore engineering [8], and urban construction [9]. Thus, applying FMECA to analyze oil pump units' failure modes and their effects

enables the identification of weak points and critical components in the units by analyzing the influence of the failures of each component on the system. This analysis provides fundamental information for evaluating and improving the reliability of the units' operation.

In practical applications, the FMECA method presents a viable solution for risk assessment. However, it has several limitations. The traditional FMECA approach employs the *risk priority number* (*RPN*) to determine the severity of a failure mode. The *RPN* is computed by multiplying the incidence, severity, and detection of the failure mode [8]. Such a method is highly subjective and prone to individual variability. Additionally, different combinations of *occurrence* (*O*), *severity* (*S*), and *detection* (*D*) can yield identical *RPN* values, and an excessively high *RPN* can make objective comparisons impractical. Consequently, these drawbacks hinder the ability of the traditional hazard analysis method to accurately convey the impact of failure modes on system reliability. This is particularly evident when analyzing oil pump units with complex failure modes.

In this paper, a method for the FMECA of oil pump units based on the Dempster–Shafer evidence theory is proposed to overcome the subjectivity and variability of the assessment by using intervals to derive the assessment of each risk factor of the unit from experts. The risk factors are combined to obtain a multi-valued characterization of the *RPN* associated with each failure mode. We optimize the belief and plausibility distributions to eliminate the existence of the same ranking of the failure mode priority ranking in some cases. Finally, we use the normalization method in statistics to obtain the risk degree ranking of failure modes and identify the critical failure modes of the oil pump units. Our results demonstrate that our proposed method is a practical risk evaluation and operation reliability analysis technique for oil pump units with significant application value.

The paper is structured as follows. In this section, the motivation of the study and the scope of discussion are introduced. The second section presents the characteristics of the traditional FMECA method and a review of the relevant literature. The third section proposes the improved FMECA method. Section IV applies the improved FMECA method to the oil pump unit. The fifth section discusses the study. Finally, a conclusion is drawn, and directions for further research are proposed.

2. Introduction of FMECA

As a safety risk analysis and assessment tool, FMECA is widely used in the industry due to the fact that it offers practical solutions. Li et al. [10] used the FMECA method to analyze the failure modes and hazard degrees of spacecrafts and calculated the hazard degrees of each failure mode using a combination of failure rate and failure impact probability to carry out guidance for improvement. The results show that the reliability analysis using the FMECA method can extend the service life of spacecraft equipment and greatly improve the usability of the equipment. Morale et al. [11] conducted a safety analysis of storage systems used in LNG regasification units using a combination of FMECA and hazard and operability analysis methods, identifying potential sources of human error in the units, causal factors in failures, multiple or common cause failures, and the causes of various failures in the process. Davide Piumatti et al. [12] provided a solution to automate the FMECA process for complex cyber-physical systems by using the FMECA approach to analyze how individual subsystem failures affecting the cyber-physical system may propagate to the entire cyber-physical system, considering both embedded software and mechanical components. Wang et al. [13] introduced the FMECA method to the missile system domain and assessed the severity, occurrence, and detection of failure modes using the common risk factor method. The obtained *RPN* values were used to guide the maintenance analysis and maintenance planning. Gizem Elidolu et al. [14] used FMECA for the risk assessment of ballasts and pressure relief operations on cruise ships and used evidential reasoning (ER) and rule-based Bayesian networks (RBN) to address the limitations of FMECA by assessing the significance of hazards. They identified that the failure mode with the highest risk level was out-of-sync cargo and ballast operations.

The FMECA method rates failure modes by combining the *severity* (*S*), *occurrence* (*O*), and *detection* (*D*), which are scores obtained using a discrete decile scale [15], as shown in Table 1 [16]. S is an assessment of the degree of damage to the system and its surroundings due to the occurrence of the failure mode, *O* is the frequency of the failure mode, and *D* is the ease with which the failure mode can be detected. The *severity* and *occurrence* of a failure mode are inversely proportional to the *detection* ranking [8]. In other words, a lower *detection* ranking suggests a higher likelihood of the failure mode not being detected. Multiplying these three risk parameters results in a measurement called the *Risk Priority Number* (*RPN*) [17]. The FMECA approach selects critical failure modes with a high risk rating based on the *RPN* values, ordering them in descending order. A higher RPN value indicates a greater risk to the system's reliability arising from the failure modes. The following equation is used to calculate the *RPN*, as described above:

$$RPN = S \times O \times D \quad (1)$$

Since its proposal, FMECA technology has been widely used in industrial fields by changing the mode of "detecting faults and repairing them" to "predicting faults and preventing them". However, despite its wide application, this traditional failure mode prioritization method (the *RPN* value method) has many defects [18].

Table 1. Criteria defined for severity, occurrence, and detection scoring in FMECA.

Rating	***Severity* (*S*)**	***Occurrence* (*O*)**		***Detection* (*D*)**
		Failure Probability (P)	**Occurrence Probability**	
10	Hazardous without warning	$P > 0.33$	Extremely high	Absolutely uncertain possibility
9	Hazardous with warning	$0.2 < P < 0.33$	Very high	Very remote possibility
8	Extreme effect	$4 \times 10^{-3} < P < 0.2$	Repeated failures	Remote possibility
7	Very high effect	$10^{-2} < P < 4 \times 10^{-2}$	High	Very low possibility
6	High effect	$2 \times 10^{-3} < P < 1 \times 10^{-2}$	Moderately high	Low possibility
5	Moderate effect	$4 \times 10^{-4} < P < 2 \times 10^{-3}$	Moderate	Moderate possibility
4	Low effect	$10^{-5} < P < 4 \times 10^{-4}$	Relatively low	Moderately high possibility
3	Minor effect	$P = 10^{-5}$	Low	High possibility
2	Very minor effect	$P = 10^{-5}$	Remote	Very high possibility
1	None	$P < 10^{-5}$	Nearly impossible	Almost certain possibility

(1) Obtaining precise values for *S*, *O*, and *D* can often be challenging. Due to the uncertainty of available information and the imprecision of human sensory recognition, one can only derive an interval value judgment instead of a quantitative assessment of certainty [19].
(2) Different evaluations of *S*, *O*, and *D* may result in the same *RPN*, even if their risk effects are completely different [19]. For example, if there are two different failure modes with *S*, *O*, and *D* values of 3, 2, and 2 and 1, 4, and 3, respectively, the *RPN* values obtained are both 12. However, the two failure modes have different severity levels, so their risk effects may be very different.
(3) The *RPN* only includes three factors related to the safety aspects of the oil pump units, so other important factors, such as economic factors, are ignored.

(4) Small changes in the evaluation of one parameter may lead to significant changes in the *RPN* results, without taking into account the relative importance of *S*, *O*, and *D* [18].

Numerous scholars have endeavored to enhance the FMECA method in response to its inherent limitations. First, the fuzzy logic approach was added to the FMECA method as a suitable alternative [20]. Bevilacqua et al. [21] proposed a modified FMECA method in which the *RPN* consists of a weighted sum of six parameters (safety, machine importance to the process, maintenance cost, failure frequency, length of downtime, and operating conditions) for which weights are determined by Monte Carlo simulations. George et al. [22] used fuzzy logic in an FMECA study to prioritize the *RPN* values associated with possible failures at LNG Receiving Terminal facilities. Buffa et al. [23] investigated the recovery system of radioactive gas in an SPES experimental facility utilizing a modified fuzzy risk priority number. By comparing it with the traditional FMECA method, the fuzzy risk priority number was shown to enhance the focus of risk assessment and improve the safety of complex systems. Wu et al. [18] used the evidence theory to measure uncertain information in order to overcome the uncertainty among risk factors and used the gray correlation projection method (GRPM) to rank the failure mode risk priorities in order to avoid the same ranking of different failure mode risks in the traditional risk priority number method, thus improving the shortcomings of the traditional FMECA method. Braglia [24] proposed a multi-attribute failure mode analysis (MAFMA) method that employs the analytic hierarchy process (AHP) technique. This method takes into account the decision criteria of risk factors (*O*, *S*, and *D*) and the expected cost of failure, decision alternatives of possible causes of failure, and decision objectives of selecting causes of failure. Cao [25] introduced a novel geometric mean failure mode and effects analysis (FMEA) method based on information quality. The method uses information quality to quantify each parameter, takes into account the correlation between individual parameters, and uses geometric means instead of arithmetic means to exclude the influence of extreme values. The method also introduces linguistic variable description techniques that allow a better representation of incomplete information and individual subjective judgments.

In contrast to the prevalent fuzzy logic approach, the utilization of the Dempster–Shafer evidence theory was introduced by Yang et al. [26]. Bae et al. [27] proposed an interval-based algorithm to improve the computational cost and applied the evidence-based *DST* to structural engineering design based on quantitative uncertainty analysis. The D-S evidence theory is used to cope with cognitive uncertainty resulting from the lack of sufficient or subjective information in the assessment process. Consequently, it is capable of managing weak knowledge, without necessitating a complete comprehension of the procedure. Within this context, this paper aims to propose a D-S evidence-based FMECA approach to minimize the limitations of traditional FMEA methods.

3. Improved FMECA Method

3.1. The Dempster–Shafer Theory of Evidence

Dempster introduced the concept of upper and lower probabilities in 1967, and subsequently carried out extended research and practical applications [28]. Subsequently, Shafer proposed a theory of evidence based on Dempster's research, which extended Dempster's synthesis rule to encompass more general cases, and, thus, became known as the Dempster–Shafer theory of evidence (i.e., D-S theory of evidence).

The method focuses on the analysis of propositions by transforming them into mathematical sets, which can contain multiple elements in the set, and differs from probability theory, which considers them only for a single element. It is precisely because of the fuzziness of the evidence theory that it can better express the uncertainty of proposition. In fact, it is more like a simulation of the normal human way of thinking, in which the first problem faced is to observe and collect information, namely, evidence. The information from all aspects is then combined to make a judgment and obtain the final result of the problem, which is evidence synthesis.

The crucial elements of the D-S evidence theory include the frame of discernment (*FOD*), the basic probability assignment (*BPA*) [29], and the Dempster combination rule.

3.1.1. Frame of Discernment

Suppose there is a problem that requires a decision, denoted by the set Θ, which represents all possible outcomes of the problem. There are mutually exclusive relations among all elements in Θ, which is finite and enumerable. At any given moment, the value of the answer to a question can only be an element in Θ. The set Θ of such incompatible events is called the *FOD* and can be expressed as follows:

$$\Theta = \{Y_1, Y_2, Y_3\} \tag{2}$$

where Y_1, Y_2, and Y_3 denote the three different propositions.

By introducing the concept of the power set, denoted as 2^Θ, 2^Θ includes all possible subsets of the proposition and the empty set Ø [30], which can be expressed as

$$2^\Theta = \{\varnothing, \{Y_1\}, \{Y_2\}, \{Y_3\}, \{Y_1 \cup Y_2\}, \{Y_1 \cup Y_3\}, \{Y_2 \cup Y_3\}, \{Y_1 \cup Y_2 \cup Y_3\}\}.$$

3.1.2. Basic Probability Assignment

After determining the *FOD*, it is necessary to establish the evidential information, which is the probability assignment corresponding to the set of propositions. For a proposition, after a comprehensive analysis of the information, a specific number can be proposed to reasonably describe the degree of support for the proposition, and this number represents the degree of beliefs assigned to the proposition. This establishes the initial assignment of propositional basic beliefs in the *FOD*, which the D-S evidence theory refers to as the basic probability assignment (*BPA*).

In *DST*, the *BPA* is indicated by the mass function (m) and assigned a value in the range of [0,1] [29], as follows:

$$m(\varnothing) = 0 \tag{3}$$

$$\sum_{pi \subseteq 2^\Theta} m(pi) = 1 \tag{4}$$

$m(pi)$ reflects the support of the evidence for the proposition pi, and its value is the basic trust assigned to the proposition. The basic trust value of the null set is 0, and the sum of the trust values of all other subsets is equal to 1. If the value of $m(pi)$ is greater than 0, then pi can be called a focal element.

3.1.3. Belief Measure and Plausibility Measure

The belief measure *Bel* (pi) expresses the confidence degree in proposition pi. It is calculated by the sum of all the *BPAs* of pk, which are the appropriate subsets of the set pi of interest [29], as follows:

$$Bel\ (pi) = \sum_{pk \subseteq pi} m(pk),\ \forall pi \in \Theta \tag{5}$$

The plausibility measure *Pl* (pi) expresses the degree of certainty about pi. It is calculated by the sum of all the *BPAs* of pk that intersect with the set of interest pi [30]:

$$pl\ (pi) = \sum_{pk \cap \mathrm{pi} \neq \varnothing} m(pk),\ \forall pi \in \Theta \tag{6}$$

Pl (pi) contains the basic confidence of all those sets that are compatible with pi, so *Pl* (pi) is a more relaxed estimate than *Bel* (pi). It can be concluded that $Bel\ (pi) \leq Pl\ (pi)$, and the relationship between *Bel* (pi) and *Pl* (pi) is as follows:

$$pl\ (pi) = 1 - Bel\ (\overline{pi}) \tag{7}$$

where $\overline{pi}$ denotes the complement of *pi*.

The D-S theory of evidence uses the interval [*Bel* (*pi*), *pl* (*pi*)] to represent the uncertainty confidence interval for the proposition, indicating the degree of uncertainty of the evidence. This interval is composed of the belief measure and the plausibility measure. *Bel* (*pi*) denotes the lower limit of the exact probability at which *pi* is supported, and *Pl* (*pi*) denotes the upper limit of the exact probability at which *pi* is supported [30], and their relationship is shown in Figure 1.

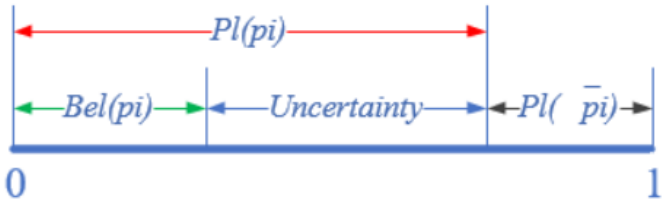


Figure 1. *Bel* (*pi*) and *Pl* (*pi*) relationship.

3.1.4. Dempster Combination Rule

Bel_1 and Bel_2 are two belief measures on the same *DST*, and m_1 and m_2 are their corresponding mass function with focal elements p_a and p_b, respectively.

$$K = \sum_{P_a \cap P_{b=\varnothing}} m_1(p_a) \cdot m_2(p_b) \tag{8}$$

$$m(pi) = \begin{cases} 0 & pi = \varnothing \\ \frac{\sum_{P_a \cap P_{b=\varnothing}} m_1(p_a) \cdot m_2(p_b)}{1-K} & pi \neq \varnothing \end{cases} \tag{9}$$

Equation (9) is the Dempster combination rule of two belief measures [31]. The resulting synthesized *m*(*pi*) is called the direct sum of m_1 and m_2, denoted as $m_1 \oplus m_2$, and the corresponding belief measure is also called the direct sum of Bel_1 and Bel_2, denoted as $Bel_1 \oplus Bel_2$.

$(1-k)^{-1}$ is called the normalization factor, which is actually introduced to avoid the assignment of non-zero confidence to the null set when the evidence is combined, and the confidence assignment discarded by the null set is proportionally made up to the non-null set. *k* indicates the degree of conflict between the evidence, and the larger its value indicates, the greater the conflict between the evidence. When *k* = 1, then m_1 and m_2 are completely conflicting, and $m_1 \oplus m_2$ or $Bel_1 \oplus Bel_2$ does not exist.

3.2. FMECA Method Based on the Dempster–Shafer Theory of Evidence

The D-S evidence theory has been widely adopted as a mathematical model for handling cognitive uncertainty, pattern recognition, and multi-criteria decision-making in the field of reliability analysis. Therefore, this paper studies the FMECA method based on the D-S theory of evidence. This approach comprises five main steps, as illustrated in Figure 2.

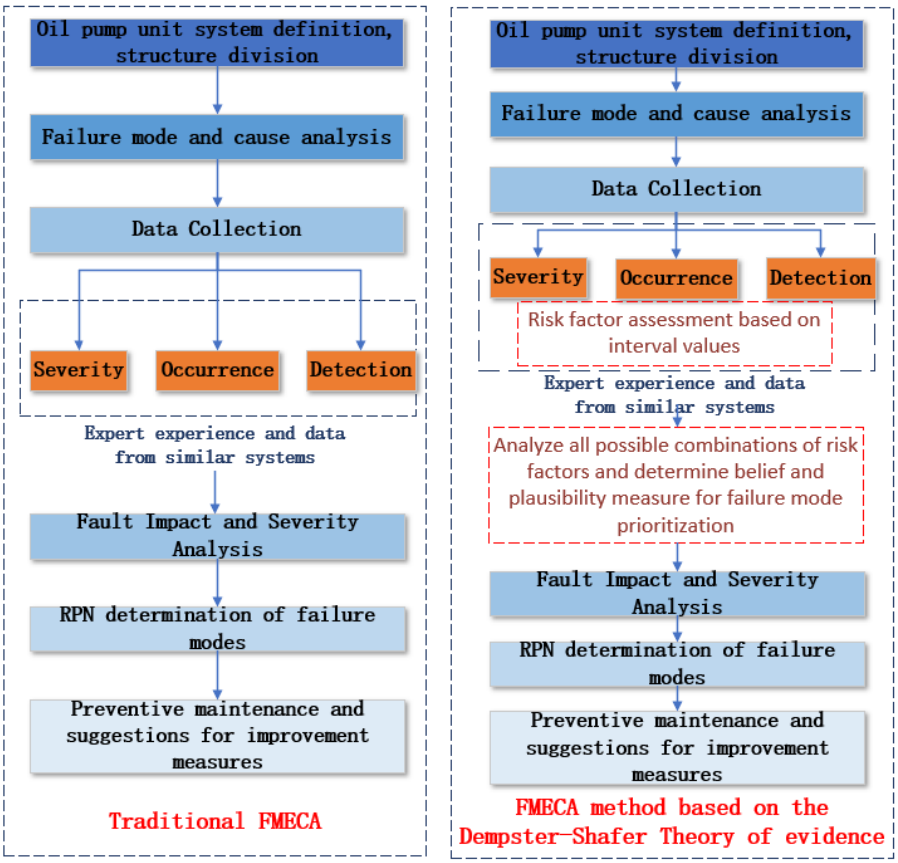


Figure 2. Comparison of FMECA method based on D-S evidence theory and traditional FMECA method.

3.2.1. Acquisition of Risk Factor Assessment Data

Compared to the traditional FMECA, the risk factors in this method are obtained from the domain experts in the form of intervals, which enables a more accurate representation of the experts' judgments, Table 2 shows that risk factors were assessed by two experts using intervals. Therefore, the three risk factors, *S*, *O*, and *D*, for each failure mode were evaluated by *N* experts in the form of intervals (see Table 1 for evaluation criteria), which were considered as discrete random variables [8]. From the *DST* perspective, this evaluation criterion defines *FODs* that are consistent with the discrete interval [1,10] for all three risk factors. Each expert's assessment of the failure mode risk factors has the same credibility, so the *BPA* of each expert regarding the *r*th risk factor ($r = S, O,$ and D) of failure mode FM_i ($i = 1, 2, \ldots, N$) is $1/N$ [28] is represented as follows:

$$m_{i,r,fm}(X) = \frac{1}{N},\ i = 1, 2, \ldots, N$$

where $X \in P_\Theta$.

This means that the total available evidence for the *r*th risk factor of failure mode FM_i ($\sum_{X \subseteq p_\Theta} m_{i,r,fm}(X)$) is equally distributed among *N* experts and sums to 1.

Table 2. Experts' judgments on risk factors.

Experts	*S*	*O*	*D*
A	[2,3]	[3,4]	[1,2]
B	[1,2]	[1,3]	[2,3]

3.2.2. Calculating *RPN* Values for All Portfolios of Risk Factors

After obtaining the failure mode risk assessment data from the experts, all combinations of risk factor assessment results need to be considered in order to compare the failure mode risk priorities more clearly. Since there are r risk factors for failure mode FM_i judged by N experts, the number of possible combinations is N^r [29]. The *RPN* values associated with each failure mode are calculated using Equation (1), as shown in Table 3.

Table 3. Possible combinations among *O*, *S*, and *D* judgments.

Combination Number	*S*	*O*	*D*	*RPN*
1	[2,3]	[3,4]	[1,2]	[6,24]
2	[2,3]	[3,4]	[2,3]	[12,36]
3	[2,3]	[1,3]	[1,2]	[2,28]
4	[2,3]	[1,3]	[2,3]	[4,27]
5	[1,2]	[3,4]	[1,2]	[3,16]
6	[1,2]	[3,4]	[2,3]	[6,24]
7	[1,2]	[1,3]	[1,2]	[1,12]
8	[1,2]	[1,3]	[2,3]	[2,18]

3.2.3. Belief and Plausibility Distributions

In order to make the ranking of the risk priorities of the failure modes more effective, the RPN_{fm} value of failure mode *fm* needs to be compared with the generic threshold RPN^*_{fm}.

Assuming event $\overline{E} = \{RPN_{fm} > RPN^*_{fm}\}$, since an increase in the *RPN* value means an increase in the hazard of the failure mode, event $\overline{E}$ matches the description of the hazard of the failure mode exactly. So, the larger the value of event $\overline{E}$, the more severe the hazard of the failure mode [8].

Then, for each failure mode *fm*, the belief and plausibility distributions of the $\overline{E}$ event is plotted in accordance with the N^3 RPNs obtained. The upper and lower bounds of each RPN_{fm} interval are arranged in ascending order.

The belief of the complementary event, $E = \{RPN_{fm} \leq RPN^*_{fm}\}$, is determined by the sum of $m(RPN_{fm})$ within the interval $[0, RPN^*_{fm}]$, and it is expressed by Equation (10):

$$Bel\ (E) = Bel\left(RPN_{fm} \leq RPN^*_{fm}\right) = \sum_{RPN_{fm} \in [0, RPN^*_{fm}]} m\left(RPN_{fm}\right) \quad (10)$$

The plausibility of the event $E = \{RPN_{fm} \leq RPN^*_{fm}\}$ is determined by the sum of $m(RPN_{fm})$, which intersects with $[0, RPN^*_{fm}]$, and it is expressed by Equation (11):

$$pl\ (E) = pl\left(RPN_{fm} \leq RPN^*_{fm}\right) = \sum_{RPN_{fm} \cap [0, RPN^*_{fm}] \neq \varnothing} m\left(RPN_{fm}\right) \quad (11)$$

Therefore, the belief and plausibility distributions of the $\overline{E}$ event are given in Equations (12) and (13):

$$Bel\ (\overline{E}) = Bel\left(RPN_{fm} > RPN^*_{fm}\right) = 1 - pl\left(RPN_{fm} \leq RPN^*_{fm}\right) \quad (12)$$

$$pl\ (\overline{E}) = pl\left(RPN_{fm} > RPN^*_{fm}\right) = 1 - Bel\left(RPN_{fm} \leq RPN^*_{fm}\right) \quad (13)$$

3.2.4. Failure Mode Risk Prioritization

To calculate the threshold RPN_{fm}^{*}, assuming a belief quality of $\overline{m}$, the threshold RPN_{fm}^{*} of each failure mode fm_i is derived from the intersection of $pl\left(\overline{E}\right)$ with the line $y = m$. All RPN_{fm}^{*} obtained are sorted in descending order, thus ranking the failure modes from the most critical to the least critical.

After completing the failure mode RPN_{fm}^{*} ranking, if there are multiple failure modes with the same criticality level, the intersection of the line $x = RPN_{fm}^{*}$ with $Bel\left(\overline{E}\right)$ is taken, and the hazard level of the failure mode depends on the confidence value obtained. The hazard levels are ranked in descending order according to the confidence value. A flow chart of failure mode prioritization is shown in Figure 3.

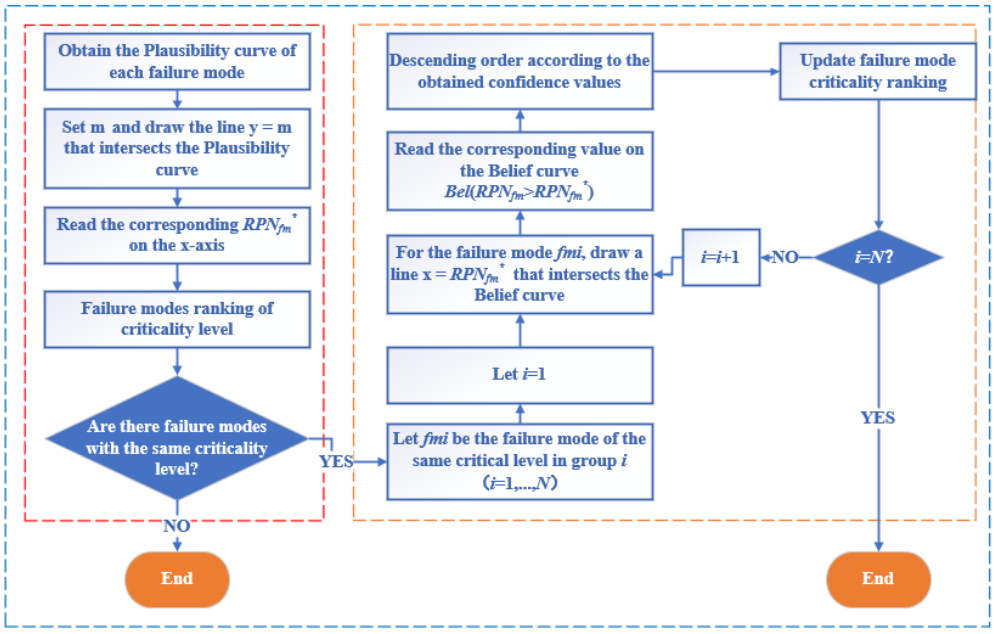


Figure 3. Flow chart of failure mode prioritization.

3.2.5. *RPN* Normalization Process

After the criticality ranking of failure modes has been determined, the *RPN* is assigned within a range of 1 to 1000. However, the *RPN* values are widely dispersed and can be difficult to compare objectively.

In order to eliminate the influence of the magnitude between risk factors, data standardization is required to address the comparability between data. After the raw data are processed by data normalization, each risk factor is in the same order of magnitude, which is suitable for comprehensive comparison and evaluation. Among them, the most typical one is the normalization of data.

Generally, data are commonly normalized to the interval of 0~1 or −1~1, but, combined with the definition of oil pump unit failure mode severity, this paper normalizes the *RPN* to the interval of 1–10, and the steps are as follows:

(1) First, find the minimum value *Min* and maximum value *Max* in the failure mode *RPN* data;

(2) Calculate the coefficient as $k = \frac{b-a}{Max-Min}$;

(3) Normalize the data to the interval $[a, b]$:$RPN = a + k\left(RPN_{fm}^{*} - Min\right)$.

4. Example Analysis of Oil Pump Unit

4.1. Failure Mode Analysis of oil Pump Unit

Based on the operational principle and the characteristics and structure of the oil pump units, the units can be divided into two major parts, namely, the motor and the pump body. The pump body part can be further subdivided into nine individual components, including bearings, couplings, pump shells, impellers, mechanical seal systems, seal rings, bushings, static seals, and sewerage pipelines.

During a field study at an oil transmission site in northeast China, the operating history and maintenance records of the oil pump units at the site for 10 years were recorded and combined with the working experience of the management and maintenance personnel at the site, and the statistical data on the major failures of the oil pump units collected by Liu et al. [32] regarding the main failure modes of the pump units can be summarized into the following failure modes: electric motor temperature increase, bearing damage, coupling misalignment, seal leakage, seal ring clearance and impeller imbalance, and other 20 failure modes [32]. These failure modes are caused for different reasons, and the various types of failure modes, causes of failure, and their effects on the system are shown in Table 4.

Table 4. Analysis of each failure mode of oil pump units.

System Name		**Failure Modes**	**Cause of Failure**	**Higher Level Influence**
Electric motors		Electric motor does not run	Power supply failure, too much voltage reduction during buck start, stator winding damage, etc.	Oil pump units do not operate
		Electric motor temperature rises	The load is too heavy, the power supply voltage is too high, the motor winding is short-circuited, etc.	Coil burns through
		High vibration and noise	Loose bearings, foreign objects enter the wind cover, operating frequency and parts resonance, etc.	Accelerated parts age
System Name	Part Name	Failure Modes	Cause of Failure	Higher Level Influence
Pump body	Bearings	High bearing temperature	Poor bearing lubrication and temperature sensor failure.	Temperature increase
		Bearing damage	Poor bearing lubrication and foreign matter enters the lubricant.	Increased vibration and temperature
		Large bearing fit clearance	Unreasonable installation.	Increased vibration and temperature
	Couplings	Coupling misalignment	Substandard installation accuracy, coupling wear, manufacturing accuracy failure, etc.	Accelerated wear of unit parts
		Damaged coupling	Violent installation, violent construction, unqualified couplings.	Accelerated parts aging
	Mechanical seal systems	High differential pressure of mechanical seal	Improper pressure adjustment.	Seal extrusion
		Mechanical seal with abnormal noise	Assembly tilt and allowable clearance is not suitable.	Seal failure
		Mechanical seal leakage	Moving ring and static ring material problems, poor processing quality of the sealing surface, etc.	Fire safety hazards exist
		High mechanical seal temperature	Clogged flushing lines and coking inside the seal.	Seal failure
	Static Seals	Static seal damage	Seal aging and long running time.	Seal leaks
	Bushings	Bushing wear	Poor lubrication, long running time, and contains impurities.	Increased vibration and temperature
	Sewerage pipelines	Sewage pipeline blockage and leakage	Long running time, sand holes, and impurities.	Temperature rise and oil leakage

Table 4. *Cont.*

System Name	Failure Modes	Cause of Failure	Higher Level Influence
Seal rings	Seal ring clearance	Poor alignment, small gap between the wear ring, dirty media, etc.	Decrease in efficiency
Pump shells	Pump shell leakage	Crack or sand holes.	Oil leakage
	Pump shell wearing	Too long of a running time.	Increased vibration and temperature
Impellers	Impeller wear and clogging	Long running time or impurities in the medium.	Decrease in efficiency and increase in vibration
	Impeller cavitation and imbalance	Pump inlet pressure is less than the saturated vapor pressure at the fluid delivery, temperature, and wear and tear.	Decrease in efficiency, increase in vibration, and increase in noise

4.2. Risk Factor Assessment

A comprehensive risk assessment of the oil pump unit was conducted based on the proposed FMECA method of the D-S theory of evidence. To account for the uncertainty and ambiguity of the evaluation subject, intervals were utilized in assessing the failure mode risk factors. The failure mode analysis of the oil pump unit, combined with the assessment of its severity and detection from three experienced experts in this field and the related failure maintenance records, resulted in the failure mode risk factor assessment table of *S*, *O*, and *D* shown in Table 5.

Table 5. Risk factor assessment table.

Failure Mode Code	Failure Modes	*S*			*D*			*O*
		TM1	**TM2**	**TM3**	**TM1**	**TM2**	**TM3**	**M**
FM1	Damaged coupling	[8,9]	[8,9]	[7,8]	[4,5]	[5,7]	[5,6]	[5,6]
FM2	Electric motor does not run	[7,8]	[5,6]	[4,6]	[5,6]	[6,7]	[4,6]	[5,6]
FM3	Impeller wear and clogging	[8,9]	[6,8]	[9,10]	[5,7]	[4,5]	[6,7]	[5,6]
FM4	Impeller cavitation and imbalance	[4,5]	[5,6]	[5,7]	[5,6]	[4,5]	[4,6]	[6,7]
FM5	Seal ring clearance	[4,6]	[5,6]	[5,6]	[3,4]	[6,7]	[5,6]	[6,7]
FM6	Coupling misalignment	[5,6]	[5,7]	[4,5]	[4,6]	[5,6]	[5,7]	[6,7]
FM7	Sewage pipeline blockage and leakage	[5,5]	[6,8]	[6,7]	[7,8]	[6,7]	[5,7]	[7,8]
FM8	Electric motor temperature increase	[4,6]	[5,7]	[6,8]	[5,7]	[5,6]	[4,6]	[6,7]
FM9	High bearing temperature	[7,7]	[7,9]	[8,9]	[7,8]	[8,9]	[6,8]	[7,8]
FM10	Electric motor vibration and high noise	[7,8]	[8,9]	[6,8]	[7,8]	[6,7]	[8,9]	[7,7]
FM11	Pump shell wearing	[6,7]	[5,6]	[6,8]	[5,7]	[6,7]	[5,6]	[6,7]
FM12	Large bearing fit clearance	[7,8]	[7,8]	[6,7]	[7,8]	[5,6]	[6,7]	[6,7]
FM13	Bearing damage	[7,8]	[5,6]	[7,9]	[5,6]	[7,8]	[6,7]	[7,8]
FM14	Pump shell leakage	[6,8]	[7,8]	[8,9]	[5,6]	[6,7]	[6,8]	[6,7]
FM15	Mechanical seal leakage	[5,6]	[6,7]	[5,7]	[8,9]	[7,8]	[6,8]	[9,9]
FM16	High differential pressure of mechanical seal	[5,6]	[6,7]	[7,8]	[2,3]	[1,2]	[2,4]	[5,7]
FM17	Mechanical seal with abnormal noise	[6,7]	[5,7]	[4,5]	[5,6]	[6,7]	[6,7]	[6,7]
FM18	Bushing wear	[7,8]	[7,8]	[6,8]	[7,9]	[6,7]	[7,8]	[7,8]
FM19	High mechanical seal temperature	[8,9]	[8,9]	[6,7]	[6,7]	[7,8]	[7,9]	[7,8]
FM20	Static seal damage	[8,9]	[6,7]	[6,8]	[8,9]	[6,7]	[7,8]	[7,7]

4.3. Risk Factor Combination Calculation

Three experts were involved in the evaluation of each failure mode, so, for each failure mode, the *BPA* of its expert judgment is 1/3. In determining the *RPN* values, all possible

combinations of risk factors were considered so that a total of 3^2 combinations were counted, that is, nine combinations. Table 6 shows the nine combinations of failure mode *FM9*, and the belief and plausibility curves are plotted based on the nine combinations obtained. This is shown in Figure 4.

Table 6. Combination of *RPN* calculations for failure mode *FM9*.

Failure Mode	Combination Number	*S*	*D*	*O*	RPN_{fm}	RPN^*_{fm}
FM9	1	[7,7]	[7,8]	[7,8]	[343,448]	448
	2	[7,7]	[8,9]	[7,8]	[392,504]	
	3	[7,7]	[6,8]	[7,8]	[294,448]	
	4	[7,9]	[7,8]	[7,8]	[343,576]	
	5	[7,9]	[8,9]	[7,8]	[392,648]	
	6	[7,9]	[6,8]	[7,8]	[294,576]	
	7	[8,9]	[7,8]	[7,8]	[392,576]	
	8	[8,9]	[8,9]	[7,8]	[448,648]	
	9	[8,9]	[6,8]	[7,8]	[336,576]	

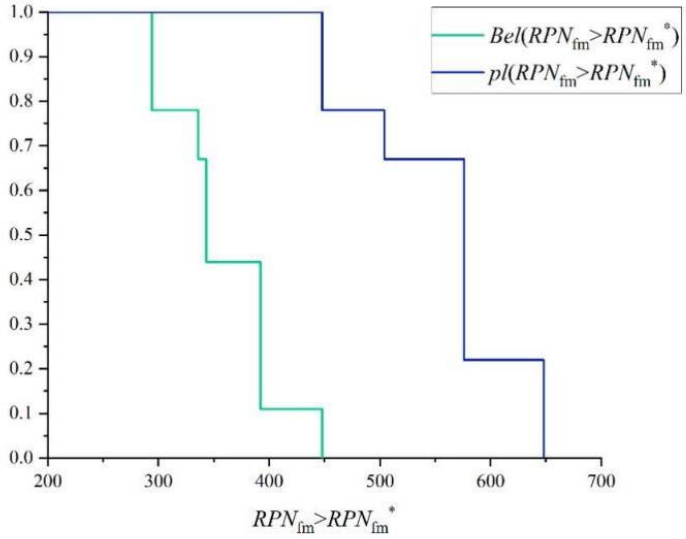


Figure 4. Belief and plausibility curves of failure mode *FM9*.

4.4. Ranking the Risk Level of Failure Modes Based on Belief and Plausibility

The mass of evidence m of each failure mode is set to 0.9 [28], and the RPN^*_{fm} of the failure mode FM_i is derived from the intersection of $pl(RPN_{fm} > RPN^*_{fm})$ and the line $y = m$. The RPN^*_{fm} of each failure mode is determined and ranked by the magnitude of the value. The relevant ratings are presented in Table 7, from which it can be seen that the failure mode *FM9* is the most critical. Moreover, it can be seen that there exist failure modes with the same RPN^*_{fm}.

Table 7. Ranking of risk level of failure modes based on belief and plausibility curves.

Failure Modes	RPN^*_{fm}	Ranking
FM9	448	1
FM15	432	2
FM10	392	3

Table 7. *Cont.*

Failure Modes	RPN^*_{fm}	Ranking
FM19	392	3
FM20	343	5
FM18	336	6
FM14	336	6
FM12	294	8
FM13	288	9
FM7	280	10
FM3	270	11
FM8	252	12
FM11	252	12
FM1	240	14
FM2	216	15
FM6	210	16
FM17	210	16
FM4	175	18
FM5	168	19
FM16	84	20

4.5. Final Ranking of Risk Level of Failure Modes Based on Belief and Plausibility Curves

For failure modes with the same RPN^*_{fm}, a straight line is drawn parallel to the y-axis from point $x = RPN^*_{fm}$. The intersection of the straight line with the confidence curve $Bel(RPN_{fm} > RPN^*_{fm})$ gives the minimum credibility of the failure mode. Failure modes *FM14* and *FM18* have the same RPN^*_{fm}. To determine the minimum credibility of the failure mode, a red line segment with x = 336 is drawn in Figures 5 and 6, and it can be seen that $Bel(RPN_{fm14} > 336) = 0$ and $Bel(RPN_{fm18} > 336) = 0.45$. Based on the analysis, it is evident that the failure mode *FM18* holds more significance than *FM14*. Therefore, following the same methodology, Table 8 presents the final risk priority ranking.

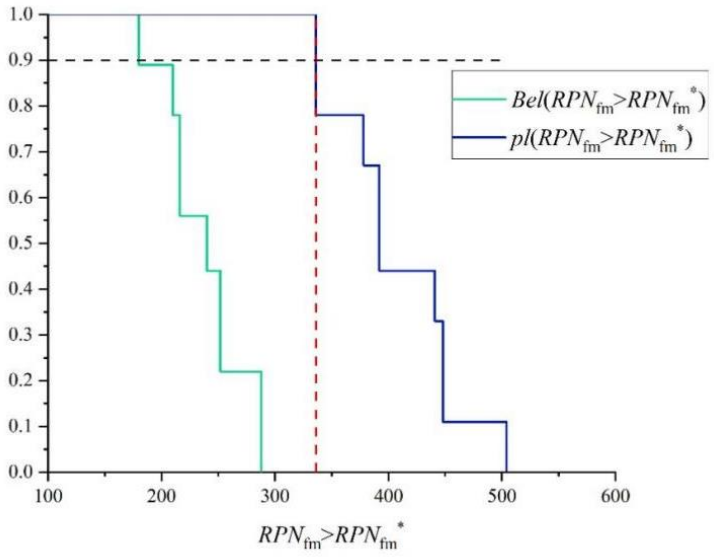


Figure 5. Belief and plausibility curves of failure mode *FM14*.

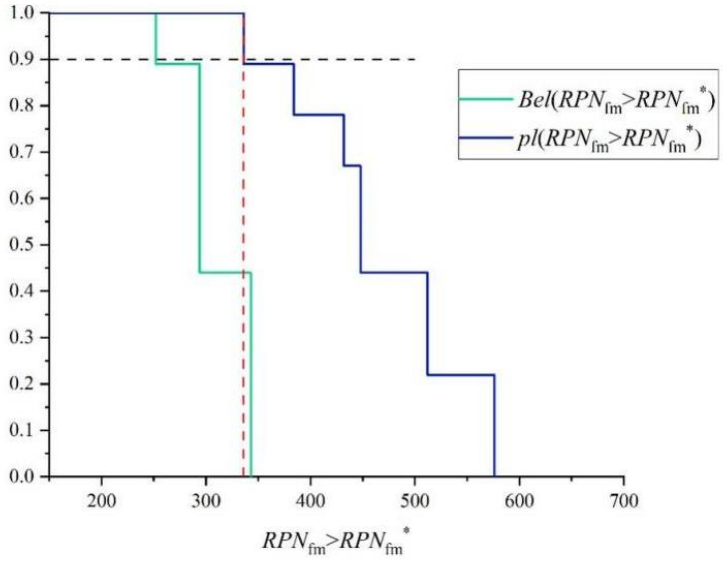


Figure 6. Belief and plausibility curves of failure mode *FM18*.

Table 8. Final rating of failure mode risk priority.

Failure Modes	RPN_{fm}^{*}	$Bel(RPN_{fm} > RPN_{fm}^{*})$ $pl(RPN_{fm} > RPN_{fm}^{*}t)$		Final Ranking
FM9	448			1
FM15	432			2
FM10	392	0.5	0.9	3
FM19	392	0	0.9	4
FM20	343			5
FM18	336	0.45	0.9	6
FM14	336	0	0.9	7
FM12	294			8
FM13	288			9
FM7	280			10
FM3	270			11
FM8	252	0.65	0.9	12
FM11	252	0.2	0.9	13
FM1	240			14
FM2	216			15
FM6	210	0.5	0.9	16
FM17	210	0	0.9	17
FM4	175			18
FM5	168			19
FM16	84			20

4.6. RPN Normalization Processing

To obtain the final ranking of the risk level for each failure mode, the *RPN* values were normalized to the interval [1, 10]. The results are presented in Table 9.

Table 9. Final ranking of risk degree of failure modes.

Failure Mode	*RPN*	Ranking
FM9	7.8400	1
FM15	7.5600	2
FM10	6.8600	3
FM19	6.8600	4
FM20	6.0025	5
FM18	5.8800	6
FM14	5.8800	7
FM12	5.1450	8
FM13	5.0400	9
FM7	4.9000	10
FM3	4.7250	11
FM8	4.4100	12
FM11	4.4100	13
FM1	4.2000	14
FM2	3.7800	15
FM6	3.6750	16
FM17	3.6750	17
FM4	3.0625	18
FM5	2.9400	19
FM16	1.4200	20

5. Discussion

In this paper, a failure mode, effects, and criticality analysis (FMECA) method based on the D-S evidence theory is proposed to analyze the potential failure modes of two systems, the motor and pump body, in an oil pump unit. The FMECA is combined with evaluations from three experienced experts in the field at the oil transmission station site and historical maintenance records of the oil transmission pump unit. The results reveal the risk priority ranking for each failure mode of the unit. The results indicate that *FM9* (high bearing temperature) is the most critical failure mode, while *FM9* and *FM15* are two failure modes with risk priority numbers greater than 7, making them the critical failure modes of the oil transfer pump unit according to Table 10. Moreover, failure modes with the same risk priority number (*RPN*) values (*FM18* and *FM4*, *FM8* and *FM11*, and *FM6* and *FM17*) are prioritized using belief and plausibility curves. Thus, bearings and mechanical seals are the key targets for the prevention and monitoring of oil pump units during operation and maintenance. This study can help involved staff at the oil transmission station to identify potential hazards present in the units and assist station safety inspectors in developing maintenance strategies accordingly. For instance, suggested maintenance actions might include installing temperature detection devices for the unit's bearing components and regularly inspecting mechanical seal circulation lines while replacing lubricating grease.

Table 10. Definitions of severity categories.

Rating	Severity Category	Severity Definition
1, 2, and 3	Mild	Failures that are not sufficient to cause early replacement of oil pump unit components but still require some unscheduled maintenance work
4, 5, and 6	Moderate	Failures that will affect the normal operation of the oil pump unit and require early repair or replacement of unit components
7 and 8	Fatal	Failures that can cause a serious drop in the performance of the oil pump unit
9 and 10	Catastrophic	Failures that can cause the oil pump unit to stop working

In classical risk-based priority sorting applications employing the *RPN* method [33,34], the *O*, *S*, and *D* factors of each fault mode are typically provided in a clear form by experts, which may not be adequate for handling uncertainties. To address this issue, we introduce FMECA coupled with the D-S evidence theory to provide a more general representation of uncertainty. Moreover, we utilize interval-based evaluations, which are particularly suited for scenarios in which there is insufficient information to define the probability distribution of an event or when the information is non-specific or subjective. In contrast to fuzzy FMECA [4,35], in which different fault modes can lead to distinct risk priority numbers but result in identical risk priority rankings, our proposed approach effectively overcomes this limitation by the use of the D-S evidence theory. Furthermore, to facilitate a more effective prioritization of risks in oil pump units, we normalize the *RPN* values of fault modes. Overall, our methodology is highly relevant for evaluating the risks associated with pump unit systems featuring complex failure modes.

6. Conclusions

Risk assessment is a crucial method for enhancing safety and reducing potential hazards in the transportation of oil and gas pipelines. This paper proposes the application of the failure mode, effects, and criticality analysis (FMECA) method based on the D-S evidence theory to conduct a detailed risk assessment of oil pump units. The method is highly applicable in evaluating safety systems in which precise and reliable information is unavailable and can overcome the cognitive uncertainty of expert judgment. It enables pump unit experts to express *O*, *S*, and *D* risk parameters using interval value judgments, thus overcoming the limitations of traditional FMECA methods expressed in clear values that may provide inconsistent expressions by different experts. Therefore, the experts' knowledge and interpretation of relevant risk factors ensure that they are handled with greater accuracy. Additionally, the method can deal with the issue of different failure modes having equal risk priority, which is caused by the better prioritization of failure mode risks, and *RPN* values are normalized, thereby enabling a more objective and reasonable risk assessment of pump unit failure modes. The practical application of this method in oil pump units has shown its effectiveness in critical failure analysis assessment and operational reliability analysis. In summary, the FMECA risk evaluation method based on the D-S evidence theory presents an efficient tool in assessing risk and can effectively improve the safety and reliability of oil pump units.

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