Improving FMEA risk assessment through reprioritization of failures

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Abstract. Most of the current methods used to assess the failure and to identify the industrial equipment defects are based on the determination of Risk Priority Number (RPN). Although conventional RPN calculation is easy to understand and use, the methodology presents some limitations, such as the large number of duplicates and the difficulty of assessing the RPN indices. In order to eliminate the afore-mentioned shortcomings, this paper puts forward an easy and efficient computing method, called Failure Developing Mode and Criticality Analysis (FDMCA), which takes into account the failures and the defect evolution in time, from failure appearance to a breakdown.

1. Introduction

To identify the possibilities of degradation for industrial equipment, different methods of analysis have been developed over time, such as Failure Tree method (FTA), Failure Mode and Effect Analysis (FMEA), Failure Mode Effect and Criticality Analysis (FMECA), Degradation Mode and Criticality Analysis (DMCA).

FTA is used to investigate potential faults, their modes and causes, and to quantify their contribution to the system unreliability in the course of product design. FTA involves the construction of a failure flowchart, through which the failure components are analyzed, including the place and cause or consequences that produce a specific type of failure [1], [2], [3].

Considering that this method does not take into account the severity of the failure, FMEA is a method used in the forecast reliability, through which the failure mode and the effect on equipment performance is analyzed [4], [5]. FMECA is an analysis method that includes the prioritization of defect consequences and the severity of the failure effect [6], [7].

DMCA is a method derived from FMEA that takes into account the loss performance and the negative effects during the reinstallation of defective equipment [8].

Although many papers have been developed related to the degradation product assessment and the identification of defects, there are, however, some limitations related to failure evolution mode that could greatly improve the prioritizing calculation of the maintenance tasks.

To overcome this limitation, the present paper proposes a new method of decision support module, called Failure Mode Developing and Criticality Analysis (FDMCA), based on data related to equipment use. FDMCA is a method that can be used successfully for operational reliability and dynamic calculation that takes into account the failures and the defect evolution in time, from failure appearance to a breakdown [9].
2. RPN methodology
In the conventional FMEA method, RPN is a methodology used to assess the risk of failure in order to prioritize the corrective maintenance actions. RPN is the mathematical product of three parameters: severity of a failure (S), probability of occurrence (O) and detectability (D), and can range from 1 to 1000. A failure mode which shows a higher RPN has a high priority for corrective action, compared to other modes of failure with lower values for RPN.
A detailed scale to rank the severity, occurrence and detection is given in tables 1, 2 and 3, respectively.

Table 1. Evaluation criteria and ranking system for the severity of effects for a FMEA design.

| Effect     | Severity of effect                                                                 | Rank |
|------------|------------------------------------------------------------------------------------|------|
| Hazardous  | Hazardous without warning, very high severity ranking. It suspends operation of the system. | 10   |
| Serious    | Failure involves hazardous outcomes with warning, very high severity ranking.         | 9    |
| Extreme    | Product is inoperable with loss of primary function. The system is not operable.      | 8    |
| Major      | The system is inoperable with equipment damage.                                     | 7    |
| Significant| Product performance is degraded. The system is inoperable with minor damage.         | 6    |
| Moderate   | System inoperable without damage. The product requires immediate repairs.            | 5    |
| Low        | Small effect on product performance. The product does not require repairs.           | 4    |
| Minor      | Minor, system operable with some degradation of performance. The product does not require repairs. | 3    |
| Very minor | Very minor effect on product or system performance. The product does not require repairs. | 2    |
| None       | No effect.                                                                          | 1    |

Table 2. Evaluation criteria and ranking system for the occurrence of failure for a FMEA design.

| Probability of failure     | Possible failure rates | Rank |
|----------------------------|------------------------|------|
| Extremely high, inevitable| ≥ 1 in 2               | 10   |
| Very high                  | 1 in 3                 | 9    |
| Repeated failures          | 1 in 8                 | 8    |
| High                       | 1 in 20                | 7    |
| Moderately high            | 1 in 80                | 6    |
| Moderate                   | 1 in 400               | 5    |
| Relatively low             | 1 in 2.000             | 4    |
| Low                        | 1 in 15.000            | 3    |
| Remote                     | 1 in 150.000           | 2    |
| Nearly impossible           | ≤ 1 in 1.500.000       | 1    |
### Table 3. Evaluation criteria and ranking system for the detection of a cause of failure for a FMEA design.

| Detection          | Detection by design control                                                                                                                                  | Rank |
|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| Absolute uncertainty | Design control does not detect the cause of failure.                                                                                                        | 10   |
| Very remote        | Very remote chance of detecting a potential cause of failure.                                                                                              | 9    |
| Remote             | Remote chance of detecting a potential cause of failure.                                                                                                   | 8    |
| Very low           | Very low chance of detecting a potential cause of failure or subsequent failure mode.                                                                     | 7    |
| Low                | Low chance of detecting a potential cause of failure.                                                                                                     | 6    |
| Moderate           | Moderate chance of detecting a potential cause of failure.                                                                                                 | 5    |
| Moderately high    | Moderately high chance of detecting a potential cause of failure.                                                                                         | 4    |
| High               | High chance of detecting a potential cause of failure.                                                                                                    | 3    |
| Very high          | Very high chance of detecting a potential cause of failure or subsequent failure mode.                                                                    | 2    |
| Almost certain     | A potential cause of failure is detected in design control almost certainly.                                                                               | 1    |

### 3. RPN shortcomings

Although conventional RPN calculation is easy to understand and use, the methodology has some limitations.

One of the most criticized considerations refers to the fact that RPN have many duplicate items. Being the product of S, O, D, RPN can take 1000 values, of which only 120 are unique values. Therefore, in calculating maintenance actions prioritization, there are many elements that occupy the same risk rank.

The second deficiency of RPN calculation is the fact that in terms of risk, RPN values are not weighted properly. Some S, O, D scenarios produce RPN values that are lower than in other combinations, but potentially more dangerous. For example, the scenario extreme severity, low rate of occurrence, high detection, which for RPN is $8 \times 3 \times 2 = 48$, is smaller than the scenario minor severity, low rate of occurrence, very remote detection, which for RPN is $2 \times 3 \times 9 = 54$, although the first case should have priority for corrective action.

A third criticized problem is that although RPN can range from 1 to 1000, there are values in the middle of the scale that can not be taken, nor are excluded from the calculation, for example multiples of 11, 13, 17, 19.

A fourth drawback of the classical method of calculating the RPN is the difficulty of assessment in the evaluation of the three indices, S, O, D. Sometimes it can be difficult or even impossible to determine the likelihood of events that lead to failure. Furthermore, the assessment of these indices is based on available information and the expertise of a specialist that can have a subjective opinion.

### 4. Failure Developing Period (FDP)

One of the most used maintenance strategy is based on the items reliability. FDP consists in analyzing the defect evolution period and the time distribution of disruptions in operation, methodology known as reliability centered maintenance (RCM).

Figure 1 represents the diagram of time interval between fault appearance and interruption in operation. Note that the defects that occur in an industrial equipment operation are divided into two categories: slowly evolving in time defects that can be discovered and prevent interruptions in operation (figure 1a) and rapidly evolving defects, for which a failure is inevitable (figure 1b).
Generally, defects related to mechanical components present an evolution in a period of time (FDP > 0), with a difference between the failure appearance and the failure of the industrial equipment (figure 1a). Once FDP is determined, the lifetime of the mechanical components can be optimized and the frequency of maintenance inspection can be planned.

![Figure 1. Failure developing period: a) slowly evolving defect; b) rapidly evolving defect.](image)

The diagram in figure 1b) is in general valid for electrical components, in the case of which a malfunction can occur rapidly, and the time for finding the related damages is very short or nonexistent (FDP = 0).

Depending on the time difference between the fault appearance and the interruption in operation, with or without the possibility of corrective intervention, on a scale of 1 to 10, FDP can take the values described in table 4.

| FDP (Failure Developing Period) | The time difference between the moment of fault and operational interruption, with the possibility / or not for corrective intervention | Rank |
|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------|------|
| Extremely fast                | The time difference between the moment of fault and operational interruption is null.                                             | 10   |
| Very fast                     | The defect is evolving rapidly, is unavoidable a reactive maintenance action.                                                     | 9    |
| Fast                          | The time difference between the moment of fault and operational interruption is very small.                                       | 8    |
| Noticeable                    | The defect evolution allows the implementation of corrective actions, if it its intervened quickly.                                 | 7    |
| Appreciable                   | The defect evolution allows the implementation of planned corrective actions.                                                        | 6    |
| Moderate                      | Planned corrective actions are applied at average intervals.                                                                          | 5    |
| Moderately slow               | Planned corrective actions are applied at large intervals.                                                                         | 4    |
| Slow                          | The defect evolution allows corrective action planning.                                                                                 | 3    |
| Very slow                     | Failure evolves very slowly.                                                                                                          | 2    |
| Extremely slow                | Failure evolves extremely slowly.                                                                                                     | 1    |
5. FDMCA method
In order to eliminate the RPN shortcomings mentioned above, this paper proposes an easy and efficient computing to enhance capacity to assess the failure risk.

In FDMCA, a Failure Risk Priority Number (FRPN) index calculation is proposed for better evaluation of the degree of criticality failure in order to prioritize the maintenance actions. FRPN is defined as a function of four indices as follows:

\[ FRPN = S \times O \times D \times FDP \]  

(1)

To demonstrate the validity of the proposed calculation method, the further major failure statements will be analyzed for the primary kinematic chain of a milling machine, in a version that includes a gearbox.

To evaluate the effectiveness of the FDMCA method, in Table 5 are presented the comparative obtained data for calculated RPN and FRPN and the rank for prioritization of corrective maintenance actions, by both methods.

The obtained results are as follows:
1. By applying the FDMCA method, the problem of the high rate of duplicates is reduced. According to the values obtained in Table 5, by conventional RPN method 23 unique values out of a total of 31 were obtained, which means a 25% duplication rate, while by the new FRPN method 27 unique values were obtained, representing a 12% duplication rate.
2. By FDMCA method, a more accurate risk classification can be obtained. On the basis of conventional RPN calculation, the elements of numbers 16 (S, O, D - 4, 7, 3), 20 (S, O, D - 6, 2, 7) and 22 (S, O, D - 7, 4, 3) have the same priority in corrective actions, with RPN = 84. Because it shows different failure modes, with different S, O, D combinations, the calculated RPN index should lead to varying degrees of risk, but in this case the priority rank for corrective actions is 17 for all three elements.

Using the new proposed FDMCA method, the FRPN values for items 16, 20 and 22 are 588, 252 and 504. This demonstrates that the three elements show varying risk degrees with different priority in ranking: 12, 20 and 14 respectively.

Table 5. Comparison between RPN and FRPN approach.

| No. | Component | Failure mode       | S  | O  | D  | FDP | RPN   | FRPN  | Ranking RPN | Ranking FRPN |
|-----|-----------|-------------------|----|----|----|-----|-------|-------|-------------|--------------|
| 1   | gearbox   | jam               | 7  | 4  | 7  | 8   | 196   | 1568  | 6           | 4            |
| 2   |          | broken teeth      | 4  | 7  | 2  | 3   | 56    | 168   | 28          | 25           |
| 3   |          | broken teeth      | 4  | 7  | 3  | 2   | 84    | 168   | 17          | 25           |
| 4   |          | broken teeth      | 4  | 4  | 3  | 2   | 48    | 96    | 30          | 31           |
| 5   |          | broken teeth      | 5  | 6  | 3  | 7   | 90    | 630   | 16          | 11           |
| 6   |          | broken teeth      | 7  | 4  | 3  | 7   | 84    | 588   | 17          | 12           |
| 7   |          | broken teeth      | 5  | 4  | 8  | 2   | 160   | 320   | 10          | 18           |
| 8   |          | broken teeth      | 5  | 3  | 8  | 2   | 120   | 240   | 14          | 22           |
| 9   |          | broken teeth      | 4  | 3  | 9  | 2   | 108   | 216   | 15          | 24           |
| 10  |          | ballads wheel     | 7  | 7  | 5  | 7   | 245   | 1715  | 4           | 3            |
| 11  |          | gear locking device wear | 5  | 2  | 5  | 2   | 50    | 100   | 29          | 30           |
| 12  |          | fastener gear failure | 5  | 3  | 5  | 3   | 75    | 225   | 24          | 23           |
| 13  |          | sliding rods damage | 5  | 2  | 8  | 2   | 80    | 160   | 22          | 27           |
The element at position 16 shows the highest degree of risk, because the failure frequency is high and the defect evolution in time requires rapid intervention from the maintenance team, in order to avoid an interruption in operation with possible damage of the entire industrial equipment.

In order of priority, the item at position 22 follows, due to the high degree of severity and occurrence of failure, compared to the element at position 20, and because of the fastest defect evolution, as well.

### 6. Conclusions

In this paper, a new FDMCA calculation method of the failure risk was implemented for the primary kinematic chain of a milling machine, in a version that includes a gearbox. The method involves the FRPN index calculation, which takes into account a parameter that defines the defect evolution in time, from the fault appearance until equipment failure.
By implementing the FDMCA, the problem of the high rate of duplicates encountered in the classical methods of analysis, which makes difficult the decision on the prioritization degree of the corrective maintenance actions, is reduced.

Also, the comparative calculation of the values obtained from failure risk rank by conventional FMEA method, leads to the conclusion that the FDMCA method is more effective in setting the priority rank. The given example indicates that by applying the new method a more accurate risk ranking for ordering the failure modes is achieved.

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