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Failure Mode and Effects Analysis: A Novel Approach Applied in a Parts Manufacturing Company

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ABSTRACT

This study proposes a new method for performing failure mode and effects analysis called Amended Failure Mode and Effects Analysis (AFMEA) based on quantitative data rather than relying on expertise, and employs the cost of various failures in order to make more accurate and cost-oriented decisions for preventive maintenance actions. Considering different failure expenses, dependability of parameters, and replication of failure causes in the new method, we put forward new formulations for calculating three main components of risk priority number (RPN). Propounding a case study from an automotive supplier, we compare the results of the traditional FMEA with the new outcomes in order to gain some experience with the modified method and analyze its usefulness. The performance of AFMEA will then be discussed and evaluated with datasets in three different periods using receiver-operating characteristics (ROC) curves. The result shows the superiority of Amended FMEA in contrast with the traditional FMEA.

KEY WORDS: Failure Mode And Effects Analysis (FMEA), Maintenance Management, Costs, ROC Analysis

1. INTRODUCTION

Reliability Centered Maintenance (RCM) is known as one of the most robust attitudes adopted for managing reliability, which was developed over a period of thirty years [1]. One of the principal milestones in its development was the report commissioned by the United States Department of Defense from United Airlines [2, 3, 4] and prepared in order to provide a comprehensive description of the development and application of RCM by the civil aviation industry [5, 6]. RCM is a process used to determine the maintenance requirements of any physical asset in its operating context. In other words, RCM is "processes used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context" [1]. It is an organized methodology employed to highlight the preventive maintenance tasks necessary to realize the inherent reliability of an item, considering the minimum resource expenditure [7].

RCM analysis principally provides a structured framework for analyzing the functions and potential failures of physical assets in order to develop a scheduled maintenance plan that will provide an acceptable level of operability, with a satisfactory level of risk, in a well-organized and cost-effective manner. RCM consists of seven major steps. Figure 1 indicates an overview of these steps and represents the impressive role of FMEA within RCM [8]. In the initial step, the equipment is selected to analyze. The next four steps, known as Failure mode and effects analysis, consist of determining the functions, describing the failures, specifying failure modes, failure effects description, and selecting appropriate maintenance or engineering actions by means of RCM logic. Failure modes are the possible ways and/or modes in which an asset can fail. Effects analysis comprises foreseeing the consequences of each failure mode [9].

2. Failure mode and effects analysis

Developed in 1949 by the American Army for evaluating the impact of system and equipment failures on mission success and the safety of personnel and equipment, Failure mode and effects analysis (FMEA) has been frequently used as a source for preventive maintenance and is recognized as significant method for designing and prioritizing preventive maintenance tasks. It is ordinarily used to design maintenance routines by analyzing potential failures, predicting their effects, and facilitating preventive actions [10]. The purpose of the FMEA is to identify the results, or effects, of an item's failure on systems operation and classify each potential failure according to its severity [11].

Failures analyses are derived from the results of the Brainstorming session (as a traditional way of implementing FMEA) and proposed engineering controls recorded manually onto hard copies or into spreadsheets. Hence, FMEA reports consist of valuable engineering information and one must know how the information could be reprocessed to avoid reoccurrence of similar failures. Nonetheless, the traditional approach has a serious setback. The method used to record FMEA report is not suitable for reuse.

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Figure 1. RCM process overview and FMEA as part of the RCM process

In fact, "When the FMEA grows, the information will be increasingly difficult to find". Since the existing attitude is believed to be time-consuming and complex, there are some scientists having the approach criticized [3]. Nonetheless, this technique is generally presented as one of the key advanced maintenance methods [1, 12].

3. LITERATURE REVIEW

Despite having FMEA extensively studied, the recent works in existing literature principally cover advancements in FMEA procedure and concept design, concerning the use of FMEA in either maintenance planning practically or adopting implicitly/explicitly based assumptions [13, 14]. Recent papers also survey the applications of FMEA in process and aerospace industries and energy systems [15]. FMEA has been even applied in therapeutic centers such as hospitals and clinics in order to analyze patient safety reduce injuries, manufacture of drugs, and in preventing medication errors in hospitals [16, 17]. While evaluating the risk of failure, three factors are frequently taken into consideration: severity, probability of occurrence, and probability of detecting the failure [9, 18]. These factors are estimated through expert judgment. The literature shows that previous works propound approaches, which reduce the dependency of FMEA on expert judgment and, therefore, makes it more appropriate for continuous improvement [19]. Most of the existing literature focused on quantifying the severity of failures and relationships between failures, sometimes including cost consequences.

Monitoring the probability of occurrence, the dependability of different failure causes, the replication of failures, and considering the effects of different periods in an asset's failure have received little attention on the literature. Our study suggests a new calculation procedure, which covers the mentioned shortcomings in preceding appraisals.

4. Problem Definition

FMEA is a way to help companies detect failures before their occurrence and perform predictive actions. Unlike its several benefits, using failure mode and effects analysis can potentially be disadvantageous since compound failure effects cannot be analyzed, successful completion of the method requires expertise, experience and good team skills, and dealing with data redundancies can be difficult. Traditionally, the failures' prioritization for corrective action is implemented by developing RPN [20]. This number is calculated by multiplying together the occurrence, severity, and detection ranking factors for all process failure modes [11]. Our study aims to put forward an alternative method for RPN calculations in traditional FMEA, which has the least coherency with expertise and hence, the results of ranking RPN are more attributable. The new formulas are all quantitative, the dependability within failure causes are taken into consideration, and failure expenses are being attended. The remainder of the article includes our methodology, description of the new proposed method, experiments, and discussion.

5. METHODOLOGY

A new algorithm that is named as Amended Failure Mode and Effects Analysis (AFMEA) is proposed for calculation and assessment of RPNs. The three parallel processes respectively estimate severity, occurrence, and detection values, which will be independently illustrated in the next section. As indicated in Figure 2 with red signal, the performance of the proposed method is continuously evaluated with ROC analysis.

We consider using logistic regression analysis as a commonly used approach in order to survey the relationships between variables of a probabilistic model [21, 22]. Suppose a matrix x is available including the characteristics of assets, which possibly effects the probability of failure, and we have a column vector β that shows the effect of x on the probability of failure P [yi =1] for asset i. Assume that y and x are available and we must estimate β . The following equation displays the logistic model, which enables us to test whether the asset failure is related to the measured data. The probability of failure of asset i, is the following:

(1)
$$p[y_i = 1] = \frac{\exp(x_i \beta)}{1 + \exp(x_i \beta)}$$

Equation (1) ensures that the probability of predictions is between zero and one. For example, consider the use of penicillin (per dose) which is able to cure people. According to medicine standards, a specific dose of the penicillin may cause to cure people. On the other hand, it may be dangerous if this medicine is prescribed more than the specified dose for human beings. A medicine research corporation wants to perform a statistical analysis for this case using logistic regression. Figure 3 explicitly shows the outputs for this example.



Figure 2. Outline of the AFMEA procedure

We will also use the concept of Receiver Operating Characteristics (ROC) analysis in order to estimate the values that show the effect of x on the probability of failure of asset i. ROC graph is "a technique for visualizing, organizing, and selecting classifiers based on their performance" [23]. ROC has been encompassed for envisioning and investigating the behavior of diagnostic systems [24]. Spackman in 1989 was one of the earliest adopters of ROC graph in machine learning.

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He established the value of ROC curves in evaluating and comparing algorithms. Having a widespread literature on the application of ROC graphs in diagnostic testing, the medical decision-making community brought ROC curves attracted the attention of broader public with their scientific American articles [24]. Consider a classifier and an example. There are four possible outcomes in a ROC analysis summarized in Table 1. If the instance is positive and it is classified as positive, it is counted as a true positive. If it is classified as negative, it is counted as a false negative. On the other hand, if the instance is negative and it is classified as negative, it is counted as a true negative; if it is classified as positive, it is counted as a false positive. Fawcett [23] suggested formulas for estimating true and false positive rates:

$$(3) tp \ rate \approx \frac{Positives \ correctly \ classified}{Total \ positives}$$

$$(4) fp \ rate \approx \frac{Negatives \ incorrectly \ classified}{Total \ negatives}$$

We can plot the relationship between fp-rate and tp-rate in a ROC curve. ROC graphs are effective tools to represent the relative tradeoffs between benefits (true positives) and costs (false positives) [23].



Figure 3. Logistic relationships in the penicillin example

They are known as two-dimensional diagrams where the tp-rate can be plotted on the Y-axis and the fp-rate on the X-axis. Again, consider the penicillin example. We want to plot the ROC curve considering the cured factor as positive level. According to the available data in Table 2, the ROC curve is plotted in Figure 4. Consider "Died" here as failures. Representing the situation that failures are predicted not to happen in a certain period, the ROC curve starts at the origin and ends at (1,1), representing a situation that each asset is projected to fail in a given period [25]. Note that in the ROC Table, the row with the highest Sensitivity-(1-Specificity) is marked with an asterisk. Since ROC curve is well above a diagonal line, we conclude that the model has good predictive ability.



Table 1. Possible Outcomes in ROC Analysis



0.40

0.60

1-Specificity False Positive 0.80

1.00

0.20

6. Amended Failure Mode and Effects Analysis (AFMEA)

0.50 0.40 0.30 0.20 0.10 0.00 0.00

A. Indices and parameters

Indices

i = 1, 2, ..., n Indices of different failures occurred j = 1, 2, ..., a, $j \neq i$ Number of simultaneous failures occurred

k = 1, 2, ..., K Indices of different customers

t = 1, 2, ..., T Indices of periods

Parameters

 RPN_{QC} Quantitative, cost-oriented risk priority number

E[S] Expected value of severity

M(O) Measure of occurrence

E[D] Expected value of failure detection

 $P(E_{it}^{S})$ Probability of the effect of failure i on the system in period t

 C_{it}^{S} Cost of the effect of failure i on the system in period t

 $P(E_{ikt}^{CS})$ Probability of the effect of failure i to customer k and its impact on the system in period t

 C_{ikt}^{CS} Cost as the consequence of the effect of failure i to customer k and its impact on the system in period t,

 $C^{\scriptscriptstyle D}_{\scriptscriptstyle iit}$ Cost of interdependency between failures i and j, and their effect on the system failure in period t,

E[OF] Expected value of failure occurrence in terms of cost

E[PF] Expected value of potential failures in terms of cost

 $P(O_{it})$ Probability of occurring failure i in period t

 C_{it}^{O} Cost of occurring failure i in period t

 $P(O_{it}O_{jt})$ Conditional probability of occurring failure j, while failure i has occurred (probability of interdependency),

 C_{iit}^{O} Cost of occurring failure j as a consequence of failure i,

 $P(O_{it}O_{it})$ Probability of occurring failures i and j independently in period t

 C_{iit}^{OID} Cost of occurring failures i and j independently,

 $P(D_{it} | O_{it})$ Conditional probability of detecting failure i whilst it was occurred in period t

 n_{it}^{O} Number of failure i replications occurred in period t

 $P(D_{it} | O'_{it})$ Conditional probability of not detecting failure i whilst it was occurred in period t

 $n_{it}^{O'}$ Number of failure i replications not occurred in period t

 $P(D_{it} | D_{it}O_{it}) \& P(D_{it} | D_{it}O'_{it})$ Conditional probabilities of interdependency,

 n_{iit}^{O} ($n_{iit}^{O'}$) Replications of occurring (not occurring) failures i and j (as a consequence) simultaneously in period t,

• Decision variables

 $x_{ijt} = \begin{cases} 1, & \text{if there is interdependency} \\ & \text{between failures i and j in period t} \\ 0, & \text{Otherwise} \end{cases}$

7. CALCULATIONS

In this section, we will present our calculations scheme for the new proposed method. According to FMEA international standard, "severity is an estimate of how strongly the effects of the failure will affect the system or the user" [26]. Therefore, different failures must have various influences on either the system or the customer. On the other hand, all the impacts of failures on customers intensify the severity of failures on the system. Thus, we estimate the expected value of severity in terms of the probabilities of different failure effects on both the customer and the system. The black signal in figure 5 illustrates our suggested procedure for computing severity in AFMEA. First, the needed information are gathered from historical data. Failures are then categorized based on their replications in each period. The probability of failures to customers and their effects are estimated respectively. Finally, the expected value of severity is calculated by means of failures expenses and interdependencies. Thus, the following equation is our proposed formula for calculating severity in AFMEA:

$$E[S] = \sum_{i=1}^{n} \sum_{t=1}^{T} P(E_{it}^{S}) \cdot C_{it}^{S} + \sum_{i=1}^{n} \sum_{t=1}^{K} P(E_{ikt}^{CS}) \cdot C_{ikt}^{CS}$$

+
$$\sum_{i=1}^{n} \sum_{j=1}^{a} \sum_{t=1}^{T} (C_{it}^{S} + C_{ijt}^{D}) x_{ijt}, \quad i \neq j$$

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The first term of the above equation estimates the severity of failures of which independently have influences on the system, the second term determines the effect of failures to customers and their impact on the system in terms of cost. Whenever the effects of failures to customers occur, the total cost of failures will intensify by an interdependency cost in addition to the system's failure costs. This is shown in the last term of equation (5) using a Boolean variable.

Occurrence is defined as the probability or frequency of the failure occurring [27]. In other words, occurrence is "the likelihood of failure or relative number of failures, expected during the item's useful life" [28]. Hence, according to the proposed procedure shown in figure 6, occurrence is estimated through equation (6), as a ratio of occurred failures to all the potential failures, in terms of their probabilities and related costs.

$$M(O) = \frac{E[OF]}{E[PF]}$$

$$E[OF] = \sum_{i=1}^{n} \sum_{t=1}^{T} P(O_{it}) . C_{it}^{O} + \sum_{i=1}^{n} \sum_{j=1}^{a} \sum_{t=1}^{T} P(O_{jt} | O_{it}) . C_{ijt}^{O}$$

$$E[PF] = \sum_{i=1}^{n} \sum_{t=1}^{T} P(O_{it}) . C_{it}^{O} + \sum_{j=1}^{n} \sum_{t=1}^{T} P(O_{jt}) . C_{jt}^{O} + \sum_{i=1}^{n} \sum_{t=1}^{a} \sum_{t=1}^{T} [P(O_{it} . O_{jt}) . C_{ijt}^{OD} + P(O_{it} | O_{jt}) . C_{ijt}^{O}], i \neq j$$

The above formulas calculate a measure for occurrence in AFMEA method, based on the different probabilities for various situations and their related costs. The two terms of equation (6-1) respectively calculate expected values for the occurrence of failures and the interdependency of occurrences based on their specified costs.

The last term which is needed to estimate RPN in our new method, is detection, which has been defined as "an estimate of the chance to identify and eliminate the failure before the system or customer is affected" [26]. Therefore, we consider a combination of different possibilities and their correlated replications through the following formula for estimating "detection" according to Figure 7 in AFMEA method.



Figure 5. "Severity" calculation procedure in AFMEA

Calculating the main three parameters of risk priority number using equations (5), (6), and (7), RPN is estimated through the following formula:

$$RPN_{OC} = E[S] \times M(O) \times E[D]$$



Figure 6. "Occurrence" calculation procedure in AFMEA

The outputs from the above equation consist of cost-oriented values used as a basis for ranking various failure modes in AFMEA method. As all the calculations are based on quantitative data and the procedure has the least coherency to experts' judgment and qualitative gathered data, this is one of the most important prominences of our proposed AFMEA method in contrast with the traditional FMEA. Accordingly, we brought forward a case study in which we have practically used AFMEA in order to evaluate its performance and discover its constructive consequences.

The RPN ranking orders of the AFMEA method is different from the traditional one, as we have included the cost criterion in calculation of RPN and, therefore, the ranking is based on the quantitative parameters rather than quantitative data.

8. CASE STUDY

Consequently, we conducted a pilot project cooperating with an automotive supplier. The company's products are supplied to Iranian car manufacturing companies and some Middle-Eastern car manufacturers for some certain products such as Peugeots, Renaults, Mazda, and so on.



Figure 7. "Detection" calculation procedure in AFMEA

The traditional FMEA method has been previously executed for the company and some causes and their effects were specified in cooperation with the company's experts. Figure 8 shows the main causes of occurring failures through experts' judgment. The term "SP & GW" stands for Stop Pin and Guide Washer, which are of the main components performing important roles in the clutch of vehicles. Each of the indicated failures has subsequent causes for which the traditional FMEA procedure has been performed and the results are extracted in Table 3.

Determining the old ranking orders with traditional FMEA, we then used our AFMEA method to calculate quantitative-cost oriented RPN for failures. Figure 2 shows the outline of our procedure. We first calculated the required parameters, which is needed for estimating three main components of RPN computation in AFMEA. The results of our calculations are extracted in Table 4.

9. RESULTS AND DISCUSSIONS

In this section, the performance of our proposed method is evaluated through Receiver Operating Characteristics (ROC) curve. Three series of datasets have been used from three different periods: short-term, medium-term, and long-term. Sample datasets are available in Appendix A. To conduct a logistic regression and use ROC curves, we need true positive and false positive rates, which are obtained using equations (3) and (4). Eleven series of failure data has been used for AFMEA short-term performance evaluation and the outcome of logistic regression are displayed in Figure 9.



Figure 8. Pareto chart for different failures in descending order of their impact

Failure No.	Failure cause	S	0	D	RPN	Ranking Order
1	Stamping force decreased	6	14	3	252	3
2	Thermal stresses too high	6	8	6	264	2
7	Press pressure effect too high	10	3	8	240	4
8	Stop pin not soldered on clutch sub element	7	5	9	315	1

	Fable	3. Resul	lts of tra	ditional FM	EA: calculation	n of RPN	(extraction)
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There are two factors in ROC curve determining how perfectly the proposed model predicted failures (perfect fit): the flow pattern of sorted data and the area under ROC curve. "If the model perfectly rank orders the response values, the curve will move most of the way to the top in spite of moving at all to the right". The area under curve indicates the goodness of fit. The following figure has an AUC=0.77778 which is appropriate for this amount of data. Table 5 illustrates our calculations in details for the short-term datasets.

10. CONCLUSIONS

Failure mode and effects analysis is a way to help companies detect failures before their occurrence and perform predictive actions. We proposed a new method, which is called amended failure mode and effects analysis (AFMEA) which is based on the cost of occurring various failures instead of expertise and we developed formulas for calculating RPN, considering the replication of failures. The suggested procedure for AFMEA and its formulations are ideal because of having in regard failure expenses, dependability among parameters, and repetition of different failures. The most important advantage of our study is quantifying all three components for computing risk priority numbers by means of cost-oriented formulations. We compared the results of the traditional FMEA with the results of our improved method in order to evaluate its effectiveness and to obtain some proficiencies with the modified method. Then, the performance of the model was evaluated using ROC curves. Table 6 briefly characterizes the outcomes of our study in contrast with the previous studies in this area.

Different customers may have various reactions against externally detected failure causes (failures that discovered by consumer after delivery of the product). Therefore modelling and considering different reactions of customers and their impact on failure expenses in AFMEA, is worthwhile. Moreover, future research could focus on the application of utilizing various approaches to evaluate the effectiveness of the proposed method.



Figure 9. Logistic regression for short-term datasets

Га	b	le 6	. C	Comparing	AFMEA	A method	with ot	her pro	posed	l mod	els
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Study or method		Feature					
	Failure severity	Failure occurrence	Failure detection	Severity parameters' dependability	Occurrence and detection parameters' dependability	Cost criterion in failure severity	Cost criterion in failure occurrence
AFMEA	✓	✓	✓	√	Ý	√	√
Franceschini & Galetto (2001)	\checkmark					\checkmark	
Teoh & Case(2005)	✓						
Bekiaris & Stevens (2005)	\checkmark						\checkmark
Von Ahsen(2008)	\checkmark				\checkmark	\checkmark	
Braaksma et al. (2012)	✓	✓				✓	\checkmark

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