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Multi-factor failure mode critically analysis using TOPSIS

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Abstract

The paper presents a multi-factor decision-making approach for prioritizing failure modes as an alternative to traditional approach of failure mode and effect analysis (FMEA). The approach is based on the 'technique for order preference by similarity to ideal solution' (TOPSIS). The priority ranking is formulated on the basis of six parameters (failure occurrence, non-detection, maintainability, spare parts, economic safety and economic cost). The Shannon's entropy concept has been used for assigning objective weights to maintenance parameters. The application of the approach has been reported with an actual case from a paper industry to illustrate the use of the proposed methodology.

Keywords: Maintenance; TOPSIS; Decision Support System; FMECA; MCDM

1. Introduction

In the present era, there has been tremendous pressure on manufacturing and service organizations to remain competitive and provide timely delivery of quality products. The managers and engineers have been forced to optimize the performance of all systems involved in their organizations. The deterioration and failure of these systems might incur high costs due to production losses and delays, unplanned intervention on the system and safety hazards. In order to avoid such situations, an appropriate maintenance policy strategy is necessary in order to repair/replace the deteriorated system before failure. Deciding on the best maintenance policy is not an easy matter, as the maintenance program must combine technical requirements with the management strategy. A good maintenance program must define maintenance strategies for different facilities. The failure mode of every component must be studied in order to assess the best maintenance solution, in accordance with its failure pattern, impact and cost on the whole system. This information helps the maintenance personnel in deciding the best-suited maintenance action and assigning the different priorities to various plant components and machines. The management of large number of tangible and intangible attributes that must be taken into account represents the complexity of the problem.

Several techniques have been discussed in the literature for planning maintenance activities of industrial plants. The most commonly used technique to evaluate the maintenance significance of the items/failure modes and categorizing these in several groups of risk is based on using Failure Mode Effect and Criticality Analysis FMECA. This methodology has been proposed in different possible variants, in terms of relevant criteria considered and/or risk priority number formulation. Using this approach, the selection of a maintenance policy is performed through the analysis of the obtained priority risk number.

1.1. Overview of FMECA technique

FMECA procedure is well documented in the lit-

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erature [17]. It emerged in the studies done by NASA in 1963 and then spread to the car manufacturing industry, where it was used to quantify the possible defects at the design stage of a product so that these were not passed to the customer.

The method is based on a session of systematic brainstorming aimed at uncovering the failures that might occur in the system or process [26] and is devoted to determining design reliability by considering potential causes of failures and their effects on the system under study [12, 19]. It provides an organized way of identifying criticalities based on its risks and is considered as the last point in failure investigation [14].

Traditionally, the criticality evaluation is carried out either by calculating a criticality number or developing a risk priority number (RPN). The criticality number for each item/ failure mode is computed by multiplying the failure effect probability, the failure mode ratio, the part failure rate and its operating time. This technique is used mostly in the nuclear, aerospace, and chemical industries. Whereas, the RPN criticality evaluation uses linguistic terms to rank the chance of the failure mode occurrence, the severity of its failure effect, and the chance of the failure being undetected on numerical scale 1 to 10.

The linguistic judgment scales are used to estimate the three quantities and RPN for different failure modes is obtained by simply multiplying these quantified parameters. This method is mostly preferred by the manufacturing industries such as automotive companies, domestic appliance firms, and tire companies etc [7].

Even though RPN evaluation with FMECA is probably the most popular technique for reliability and failure mode analysis, several problems are associated with its practical implementation. Besides the benefits of FMECA, there are some considerable problems, which have been addressed by many authors [10, 22, 23]. The most important problems discussed were:

- FMECA does not consider the interdependence among the various failure modes and effects.
- It considers only three kinds of attributes whereas other important aspects like economic aspects, production quantities, and safety aspects etc are not taken into consideration.
- It is assumed that the three indexes are equally important and identify situations with the same priority number characterized by different index levels.
- The assumption that the scales of three indexes; severity (S), occurrence (O) and detection (D) have the same metric and that the same design level corresponds to the same values on different index scales.
- Different sets of the three factors can produce exactly the same value of RPN, but the hidden implication may be totally different.
- Tthe method of multiplication adopted for calculating the risk priority number is questionable.

Considering the importance and complexity of the maintenance design problem it is observed that further efforts are needed for the development of effective methods, which will incorporate numerous evaluation criteria, help the maintenance staff in evaluating the impact of intangible factors in the maintenance decision making, and identify the best maintenance policy accordingly.

In this paper, a new technique based on modified FMECA along with TOPSIS is proposed to determine the Maintenance Criticality Index (MCI) and to overcome the limits of the conventional RPN, as cited above. This technique permits to take into consideration the several possible aspects concerning the maintenance selection problem (failure chances, detectability, costs and safety aspect etc). The method is based on a *technique for order preference by similarity to ideal solution* (TOPSIS). TOPSIS is a multi-attribute decision making methodology based on the measurement of the Euclidean distance of an alternative from an ideal goal. The technique has been specifically adapted to simplify the risk-assessment procedure and to allow a correct evaluation of pertinent data. The procedure for TOPSIS methodology is presented in the subsequent section.

2. Review of the maintenance criticality evaluation techniques

To overcome the limitations of the traditional FMCEA methodology, many new methods have been proposed in the literature in different possible variants, in terms of relevant criteria considered and/or risk priority number formulation. Gilchrist [13] presented a modified model of FMECA by introducing economic considerations. He considered the failure cost to form an expected cost model. Later on Ben-

Daya and Raouf [2] noted that the economic model proposed by Gilchrist, addresses a problem, which differs from the problem FMECA is intended to address. They combined the expected cost model proposed by Gilchrist with their improved RPN model in order to provide a quality improvement technique at the production stage. They also stated that the evaluation of the factor scores using 1-9 scale is not suitable and the treatment of equal importance is not practical. According to their model chance of occurrence should be more important and in their model, the chance of occurrence (with 1-9 scale) was raised to the power of 2.

Shanker and Prabhu [22] defined a new scale for failure prioritization. They introduced the concept of risk priority rank (RPR) as an alternative to the conventional RPN. The 1000 possible combinations of severity-detection-occurrence are used to represent the increasing risk by the integers 1 to 1000. Besides, for several managers a relevant FMECA weakness is due to the fact that this technique takes into account only some kinds of failure attributes, whereas important factors such as economic aspects are neglected. Braglia [7] proposed a multi-attribute failure mode analysis (MAFMA) by integrating traditional FMEA and economic considerations based on the analytic hierarchy process (AHP) technique for evaluating the criticality of a failure cause with different weights.

Many other multi-criteria decision making (MCDM) approaches are proposed in the literature. Almeida and Bohoris [1] discuss the application of decision-making theory in the field of maintenance with particular attention to multi-attribute utility theory**.** Triantaphyllou et al. [25] suggest the use of Analytical Hierarchy Process (AHP) considering only four maintenance criteria: cost, reparability, reliability and availability. Bevilacqua and Braglia [4] presented an application of the AHP technique for maintenance strategy selection in an Italian oil refinery processing plant, combining many features, which are important in the selection of the maintenance policy: economic factors, applicability and costs, safety, etc. Bevilacqua et al. [5] proposed a new methodology based on the integration between a modified FMCEA and a Monte Carlo simulation as a method for testing the weights assigned to the measure of RPNs. Bertolini and Bevilacqua [3] proposed a combined AHP and goal programming based model for maintenance strategy selection taking into account the budget and labor constraints alongwith classical FMCEA criteria.

Several authors make use of fuzzy set theory to tackle uncertainties in maintenance decision making, Chang et al. [9] discussed the use of grey theory to obtain criticality assessment. The use of fuzzy logic theory for the maintenance criticality analysis is also suggested in the literature [6, 18, 21]. Braglia [8] used standard TOPSIS approach for carrying out FMEA and for determining RPN using fuzzy triangular numbers.

3. TOPSIS methodology

TOPSIS method is a multi-criteria decision-making linear weighting technique, which was first proposed in its crisp version by Hwang and Yoon [15]. It is an improved version of Zeleny with notion “Displaced Ideal separated away from the Ideal Solution the least.” Its basic assumption is that the best solution should be as close as possible to ideal solution and the farthest from negative ideal solution. This method has been widely employed by the researchers to solve multi-criteria problems in many fields. Parkan and Wu [20] used in robot design, Jee and Kang [16] used for materials selection, Braglia [8] determined the maintenance criticality maintenance criticality index using FMEA. Deng et al [11] presented a modified approach of the TOPSIS method by using weighted Euclidean distances to ensure a meaningful interpretation of the evaluation result. The use of objective weights for financial ratios based on Shannon's entropy concept reflects the context-dependent concept of informational importance. This ensures that the evaluation result is not affected by the interdependency of criteria and inconsistency of subjective weights. This approach is used in the paper for evaluating maintenance criticality index by determining objective weights for identified criticality factors. The steps of this methodology are discussed below:

(i) Construction of the criteria comparison matrix for TOPSIS

TOPSIS starts from building a decision matrix,

$$X = \left[x_{ij} \right] \tag{1}$$

where the i^{th} alternative (i = 1,……..,n) is evaluated with respect to j^{th} criteria (j =1,……,m).

(ii) Normalization of the original criteria comparison matrix

The next step is to normalize the judgment matrix $X = \left[x_{ij} \right]$. Many approaches for the normalization have been discussed in the literature. The equation used by Deng et a1 [11] to transform the each element $\left[x_{ij}\right]$ is given below:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \qquad i = 1,2,\ldots,n \tag{2}$$

(iii) Computation of the weights of each comparison criterion

Computation of weight of each comparison criterion based on the calculation of entropy value and later on converting it into the weight is described in following two steps:

a) First to compute the entropy value of each criterion $\mathrm{C}_1, \mathrm{C}_2, \ldots., \mathrm{C}_n$

The weight of each criterion is calculated by introducing the entropy concept. Let e_j represents the entropy of the j th criterion.

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} r_{ij} \ln r_{ij} \qquad j = 1,2,\ldots,m \tag{3}$$

while $1/\ln m$ is a constant term and it keeps the value of e_j among 0 and 1.

b) Computation of the Weights $w_1, w_2, \ldots. w_n$ of each criterion.

The objective weight for each criterion is given by,

$$w_j = \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)} \qquad j = 1,2,\ldots,m \tag{4}$$

(iv) Determination of the positive ideal solution v^+ and negative ideal solution v^- of each criterion comparison

In order to derive the Performance Index (PI) of each criterion used for comparison, it is essential to calculate the Positive Ideal Solution v^+ and Negative Ideal Solution v^- of each benefit criterion and vice versa for cost criteria.

$$v^+ = (\max_i(r_{i1}), \max_i(r_{i2}), \ldots, \max_i(r_{in}))$$

$$= (v_1^+, v_2^+, \ldots, v_n^+) \tag{5-1}$$

$$v^- = (\min_i(r_{i1}), \min_i(r_{i2}), \ldots, \min_i(r_{in}))$$

$$= (v_1^-, v_2^-, \ldots, v_n^-) \tag{5-2}$$

With ‘benefit’ and ‘cost’ attributes we discriminate between criteria that the decision maker desires to maximize or minimize respectively.

(v) Computation of the distance for the criterion between ideal solutions and negative ideal solutions

To calculate the g-Euclidean distance from each alternative to v_I^+, and v_I^- the following equations are adopted:

$$d_i^+ = \sqrt{\sum_{j=1}^{m} w_j (v_j^+ - r_{ij})^2} \tag{6-1}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m} w_j (r_{ij} - v_j^-)^2} \qquad i = 1,2,\ldots,n \tag{6-2}$$

The d_i^+ represents the distance from the i^{th} criterion compared to positive ideal solution, and d_i^- is the distance from the i^{th} criterion compared to negative ideal solution.

(vi) Computation of the relative maintenance criticality index (MCI) of the ideal solution

The final ranking of alternatives is obtained by referring to the value of relative closeness to the ideal solution. For each criterion compared, the computation of the relative MCI can be calculated using the following formula:

$$MCI_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{7}$$

The MCI_i represents the performance index of i^{th} criteria, whereas d_i^+ and d_i^- represents the distances as mentioned earlier.

4. Criticality factor evaluation choice

The criticality evaluation factors choice is really a very delicate matter. In the traditional FMECA approach the parameters failure occurrence, non-detection and severity parameters are considered for evaluating maintenance criticality of a failure mode/ cause. But there are other parameters like safety, maintainability, spare parts availability and cost which also need to be taken into consideration. In the traditional FMECA approach these are assumed to be a part of broader parameter ‘severity’. Thus, in total six factors are identified for defining the maintenance criticality of a failure mode. These are: chance of failure (occurrence), chance of non-detection, reliability importance measure, maintainability, lead time for spare parts, and economic cost.

After the identification of critical factors the next step is their evaluation. This is achieved by defining a rational method to quantify the single criterion for each failure mode, based on a series of tables. In particular, every factor is divided into several classes that are assigned a different score (in the range from 1 to 9) to take into account the different criticality levels. The scores have then been defined in accordance with the experiences of the maintenance personnel of a paper plant producing more than 200 tons of paper per day. A brief description of the method and technical data used to assign the different scores is discussed in the subsequent sections.

Table 1. Scores for chance of failure.

Occurrence	MTBF	Score
Almost never	>3 years	1
Rare	2-3 years	2
Very few	1-2 years	3
Few	3/4-1 year	4
Medium	6-9 months	5
Moderately high	4-6 months	6
High	2-4 months	7
Very high	1 2 months	8
Extremely high	< 30 days	9

Table 2. Scores for Non-Detection of Failures.

Likelihood of Non-detection (%)	Criteria for non detection of failures	Score
< 10	Extremely low	1
10-20	Very low	2
21-30	Low	3
31-40	Fair	4
41-50	Medium	5
51-60	Moderately high	6
61-70	High	7
71-80	Very high	8
> 80	Extremely high	9

4.1. Chance of failure (O)

It is concerned with the frequency with which a failure mode occurs; higher value indicates higher criticality of the item. Probability of occurrence of failure was evaluated as a function of mean time between failures (MTBF). The data related to MTBF of components was obtained from previous historical records, logbooks maintained and is then integrated with the experience of maintenance personnel. Table 1 presents the probability of failure occurrence with corresponding MTBF and scores assigned.

4.2. Non-detection of Failures (D)

The chance of detecting a failure cause or mechanism depends on various factors such as ability of operator or maintenance personnel to detect failure through naked eye or by periodical inspection or with the help of machine diagnostic aids such as automatic controls, alarms and sensors (Table 2).

4.3. Maintainability (M)

Maintainability represents the ease at which particular equipment is restored back to its up state. Lower value indicates that it is not easier to put the item back to the operational state within a given time frame, so higher chances of greater down time. Thus lower the value of maintainability, greater is the criticality for maintenance. Therefore, different values of maintainability index are identified with different criticality levels of maintenance. The values of maintainability index used in the study are reported in Table 3.

4.4. Spare parts (SP)

A number of spare parts are required for maintenance. The availability of these parts will have considerable influence to describe maintenance criticality of different components. Considering the importance of spare parts, a scheme for assigning priority scores has been developed. Here the parts are classified as vital, essential and desirable, which are further grouped as scarce, difficult to obtain, and easily obtainable. The scores assigned to their mutual combinations are shown in Table 4.

4.5. Economic safety (ES)

This factor is referred to personnel, equipment and structural safety in the event of a failure. The scores are assigned according to the functionality of the parts (associated with failure mode). Since moving parts are more prone to accidents, so high scores are given to the components with more number of moving parts. A typical scheme for assigning the scores for economic safety loss is given in Table 5.

4.6. Economic cost

The determination of economic cost of a failure mode is not an easy task. So scores are assigned according to the qualitative judgment of maintenance personnel. The various aspects considered for obtaining a score table based on linguistic evaluation are production loss, spare parts costs and maintenance manpower etc. The scoring scheme is given for economic cost is given in Table 6.

Table 3. Scores for maintainability.

Criteria	Maintainability	Score
$M_t > 0.8$	Almost certain	1
$0.7 < M_t \leq 0.8$	Very high	2
$0.6 < M_t \leq 0.7$	High	3
$0.5 < M_t \leq 0.6$	Moderately high	4
$0.4 < M_t \leq 0.5$	Medium	5
$0.3 < M_t \leq 0.4$	Low	6
$0.2 < M_t \leq 0.3$	Very low	7
$0.1 < M_t \leq 0.2$	Slight	8
$M_t < 0.1$	Extremely low	9

Table 4. Scoring criteria for spare parts.

Criticality	Availability		
	Easy	Difficult	Scarce
Desirable	1	4	7
Essential	2	5	8
Vital	3	6	9

Table 5. Scores for economic safety loss.

Status of the equipment/ sub system	Score
With no moving parts	2
With one moving part/ critical category	3
With two moving parts/ critical category	5
With three moving parts/ critical category	7
With more than three moving parts/ critical category	9

Table 6. Sores for economic safety loss.

Criteria for economic cost	Score
Extremely low	1
Very low	2
Low	3
Fair	4
Medium	5
Moderately high	6
High	7
Very high	8
Extremely high	9

5. Case study

This proposed methodology is presented here with a case analysis of a paper-manufacturing unit in India. There are many functional units in a paper mill such as feeding, pulp preparation, pulp washing, screening, bleaching and preparation of paper. The current analysis is based on the maintenance study of a decker in a screening unit, which is one of the main and most important functional units of the paper mill. The purpose of the deckers is to remove the black liquor from the pulp, which is used in the digester while cocking the pulp.

Vacuum needs to be maintained in the drum of deckers while the pulp rolls on the surface of the drums. The potential failure modes of the decker, their causes and effect on performance of the system are identified through the root cause analysis (RCA). The numerical scores to various identified failures causes are assigned as per the scoring scheme discussed in the earlier section (Table 7).

Table 7. Scores assigned to failure modes of a decker unit of a paper plant.

Major Components	**Potential failure mode**	**Potential effect of failure**	**Potential cause of failure**	**O**	**D**	**M**	**SP**	**ES**	**EC**
Wire mesh	Buildup	Improper screening of pulp	Abrasion of mesh [D_1]	3	5	3	4	3	3
			Corrosion [D_2]	5	5	6	4	3	4
			Foreign material [D_3]	8	8	4	2	3	4
Vacuum pumps	Leakage rotor jamming	Loss in operational efficiency	Lack of lubrication in moving parts. [D_4]	4	5	6	4	6	5
			Bearing failure [D_5]	5	5	8	4	6	7
			Inclusion of solid particles[D_6]	5	7	5	3	6	7
			Seal failure [D_7]	8	5	6	3	3	5
Let down relief valve	Fails open	Loss in operation	Mechanical failure [D_8]	5	8	5	8	3	7
	Fails closed		Blockage [D_9]	4	7	4	7	3	6

Table 8. The Normalized Matrix.

Failure causes	**O**	**D**	**M**	**SP**	**ES**	**EC**
D_1	0.0638	0.0909	0.0638	0.1143	0.0952	0.0625
D_2	0.1064	0.0909	0.1277	0.1143	0.0952	0.0833
D_3	0.1702	0.1455	0.0851	0.0571	0.0952	0.0833
D_4	0.0851	0.0909	0.1277	0.1143	0.1429	0.1042
D_5	0.1064	0.0909	0.1702	0.1143	0.1429	0.1458
D_6	0.1064	0.1273	0.1064	0.0857	0.1429	0.1458
D_7	0.1702	0.0909	0.1277	0.0857	0.0952	0.1042
D_8	0.1064	0.1455	0.1064	0.1714	0.0952	0.1458
D_9	0.0851	0.1273	0.0851	0.1429	0.0952	0.1250

Table 9. The distance of failure causes from ideal solution.

Failure causes	**O**		**D**		**M**		**SP**		**ES**		**EC**	
	d_{i1}^{+}	d_{i1}^{-}	d_{i2}^{+}	d_{i2}^{-}	d_{i3}^{+}	d_{i3}^{-}	d_{i4}^{+}	d_{i4}^{-}	d_{i5}^{+}	d_{i5}^{-}	d_{i6}^{+}	d_{i6}^{-}
D_1	0.1064	0.0000	0.0545	0.0000	0.1064	0.0000	0.0571	0.0571	0.0476	0.0000	0.0833	0.0000
D_2	0.0638	0.0426	0.0545	0.0000	0.0426	0.0638	0.0571	0.0571	0.0476	0.0000	0.0625	0.0208
D_3	0.0000	0.1064	0.0000	0.0545	0.0851	0.0213	0.1143	0.0000	0.0476	0.0000	0.0625	0.0208
D_4	0.0851	0.0213	0.0545	0.0000	0.0426	0.0638	0.0571	0.0571	0.0000	0.0476	0.0417	0.0417
D_5	0.0638	0.0426	0.0545	0.0000	0.0000	0.1064	0.0571	0.0571	0.0000	0.0476	0.0000	0.0833
D_6	0.0638	0.0426	0.0182	0.0364	0.0638	0.0426	0.0857	0.0286	0.0000	0.0476	0.0000	0.0833
D_7	0.0000	0.1064	0.0545	0.0000	0.0426	0.0638	0.0857	0.0286	0.0476	0.0000	0.0417	0.0417
D_8	0.0638	0.0426	0.0000	0.0545	0.0638	0.0426	0.0000	0.1143	0.0476	0.0000	0.0000	0.0833
D_9	0.0851	0.0213	0.0182	0.0364	0.0851	0.0213	0.0286	0.0857	0.0476	0.0000	0.0208	0.0625

(i) Normalization of the original data evaluation matrix

The scores assigned to the factors are normalized using the Equation (2). The normalized values thus obtained are given in Table 8, which are to be used in the computation of weight in the next section.

(ii) Computation of the weight of each evaluation criterion

The weights for each factor are computed from equations (3) and (4), which are given as follows:

$w_O = 0.2297$ $w_D = 0.1085$ $w_M = 0.1788$

$w_{SP} = 0.2032$ $w_{ES} = 0.0981$ $w_{EC} = 0.1817$

The highest weight is found for failure occurrence.

(iii) Determination of the ideal solution v^+ and negative ideal solution v^- of each evaluation criterion

Since our aim is to find the most critical failure cause so cost criteria is chosen here. Let us suppose v^+ represent the ideal solution (i.e. the most critical-failure cause) and v^- represents the negative one (i.e. the least preferred). The values obtained using Equations (5-1) and (5-2) are given as follows:

$$v^+ = (v_1^+, v_2^+, v_3^+, v_4^+, v_5^+, v_6^+)$$

$$= (0.1702, 0.1455, 0.1702, 0.1714, 0.1429, 0.1458)$$

$$v^- = (v_1^-, v_2^-, v_3^-, v_4^-, v_5^-, v_6^-)$$

$$= (0.0638, 0.0909, 0.0638, 0.0571, 0.0952, 0.0625)$$

(iv) Computation of the distances between the evaluation subjects, ideal solutions and negative ideal solutions and performance index

Using Equations (6-1) and (6-2), the various distances are obtained which indicates position of the different failure causes for each factor from ideal solution and negative ideal solution (Table 9). These distances are used in the calculation of maintenance criticality index (MCI) to prioritize the failure modes in terms of their maintenance criticality. Table 10 shows the final ranking of failure causes on the basis of MCI obtained with this methodology using Eq. 7.

Table 10. Final Ranking of Failure Modes.

Failure cause	MCI value	Ranking
D_1	0.2342	9
D_2	0.4352	6
D_3	0.4428	7
D_4	0.4402	8
D_5	0.6070	2
D_6	0.4711	4
D_7	0.5440	3
D_8	0.6190	1
D_9	0.4609	5

6. Conclusion

This paper presents a new modified FMECA approach to deal with the problems encountered while defining the best mix of maintenance policies. An objective weighted function based multi-criteria failure mode analysis technique using TOPSIS is proposed to find more accurate and reliable priority risk numbers for performing the criticality analysis. This enables us to obtain a ranking of failure modes / components by incorporating several types of information related to performance, safety and society. In particular, the analysis of prioritization of failure causes provides a framework to decide upon the type of maintenance strategies for different failure modes. If reliable quantitative judgments are available for some criteria, then it can also be easily included in the analysis. So the use of the proposed approach forms a basis for the continuous process of reliability design and maintenance strategy decisions.

References

[1] Almeida, A. and Bohoris, G., 1995, Decision theory in maintenance decision making. *Journal of Quality & Maintenance Engineering*, 1, 39-45.

[2] Ben-Daya, M. and Raouf, A., 1996, A revised failure mode and effect analysis model. *International Journal of Quality & Reliability Management*, 13, 43-47.

[3] Bertolini, M. and Bevilacqua, M., 2006, A combined goal programming - AHP approach to maintenance selection problem. *Reliability Engineering and System Safety*, 91, 839-848.

[4] Bevilacqua, M. and Braglia, M., 2000, The analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering and system Safety*, 70, 71-83.

[5] Bevilacqua, M., Braglia, M. and Gabbrielli, R., 2000, Monte Carlo simulation approach for a modified FMECA in a power plant. *Quality and Reliability Engineering International*, 16, 313-324.

[6] Bowles, J.B. and Pelaez, C.E., 1995, Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. *Reliability Engineering and System Safety,* 50, 203-213.

[7] Braglia, M., 2000, MAFMA: Multi-attribute failure mode analysis. *International Journal of Quality & Reliability Management*, 17, 1017-1033.

[8] Braglia, M., Frosolini, M., and Montanari, R., 2003, Fuzzy TOPSIS approach for failure mode, effects and criticality analysis. *Quality and Reliability Engineering International*, 19, 425-443.

[9] Chang, C., Liu, P. and Wei, C., 2001, Failure mode effects analysis using grey theory. *Integrated Manufacturing Systems,* 12(3), 211-216.

[10] Dale, B.G. and Cooper, C., 1992, *Total Quality and Human Resources: An Executive Guide*, Blackwell Publishers, Oxford.

[11] Deng, H., Yeh, C. and Willis, R.J., 2000, Inter-company comparison using modified TOPSIS with objective weights. *Computers & Operations Research*, 27, 963-973.

[12] Dillon, B.S., 1985, *Quality Control, Reliability, and Engineering Design*. Dekker, New York.

[13] Gilchrist, W., 1993, Modeling failure modes and effects analysis. *International Journal of Quality & Reliability Management*, 10, 16-23.

[14] Holmberg, K. and Folkeson, A., 1991, *Operational Reliability and Systematic Maintenance*. Elsevier, London.

[15] Hwang, C.L. and Yoon, K., 1981, *Multi-Attribute Decision Making Methods and Applications*. Springer-Verlag, New York.

[16] Jee, D. and Kang, K., 2000, *A method for optimal material selection aided with decision making theory*', Materials and Design, 21, 199-206.

[17] McDermott, R., Mikulak, R. and Beauregard, M., 1996, *The Basics of FMEA*. Productivity Inc., Portland.

[18] Moss, T.R. and Woodhouse, J., 1999, Criticality analysis revisited. *Quality and Reliability Engineering International,* 15, 117-121.

[19] O'Connor, P., 1981, *Practical Reliability Engineering*. Heyden, London.

[20] Parkan, C. and Wu, M., 1999, Decision-making and performance measurement models with applications to robot selection. *Computers & Industrial Engineering*, 36, 503-23.

[21] Pelaez, C.E. and Bowles, J.B., 1994, *Using fuzzy logic for system criticality analysis*. Proceedings of the IEEE Annual Reliability and Maintainability Symposium, Anaheim, CA, 449-455.

[22] Shankar**,** N.R. and Prabhu, B.S., 2001, Modified approach for prioritization of failures in a system failure mode and effects analysis. *International Journal of Quality & Reliability Management*, 18(3), 324-35.

[23] Straker, D., 1995, *A Tool book for Quality Importance and Problem Solving*. Prentice-Hall International Limited, London.

[24] Teng, S.-H. and Ho, S.-Y., 1996, Failure mode and effects analysis: an integrated approach for product design and process control. *International Journal of Quality & Reliability Management*, 13(5), 8-26.

[25] Triantaphyllou E., Kovalerchuk B., Mann L. and Knapp G., 1997, Determining the most important criteria in maintenance decision making. *Journal of Quality & Maintenance Engineering*, 3, 16-24.

[26] Vandenbrande, W.W., 1998, How to use FMEA to reduce the size of your quality toolbox. *Quality Progress*, 31(11), 97-100.