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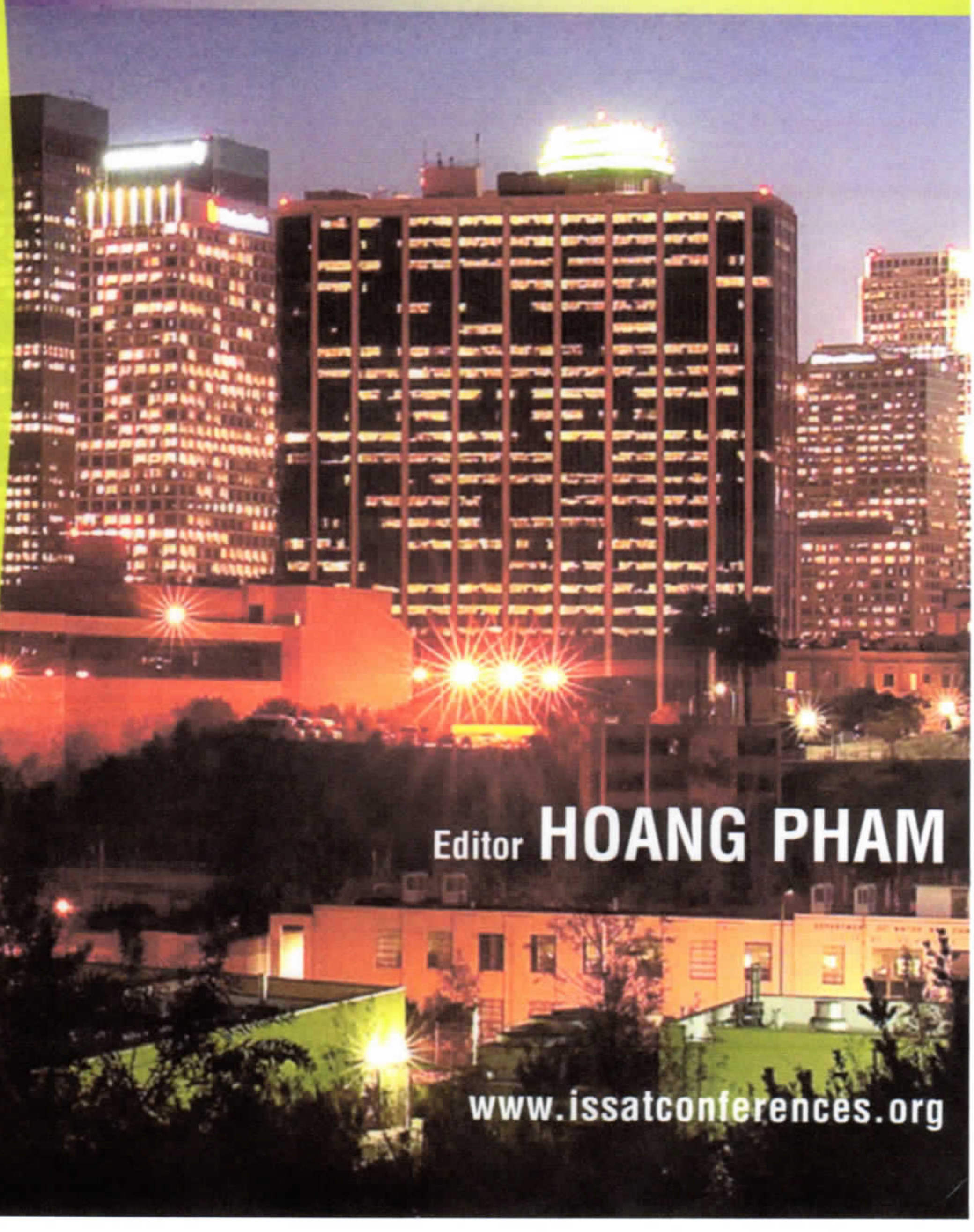

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The FTOPSIS method to support FMECA analyses

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Abstract: This paper proposes an approach based on multi-criteria decisional methods to manage the results derived from reliability analyses. In detail, this paper proposes ranking the failure modes of a system when analyzed with *failure modes, effects and criticality analysis* (FMECA) using the *technique for order preference by similarity to ideal solutions* (TOPSIS). To better manage the uncertainty of evaluations made under the differing criteria, the TOPSIS method is applied in its fuzzy version (FTOPSIS). When the method is applied to a case study, the results highlight the main possible critical faults and supply fundamental information to take into account during the scheduling of maintenance actions.

1. Introduction and literature review

Reliability analysis of complex systems, such as production and service systems [1, 2], is fundamental to reach safety objectives and generally optimize system performance [3]. This type of analysis supports various strategic actions aimed at preventing many dangerous possible faults [4]. Several techniques have been proposed in the literature for the reliability analysis of complex systems and one of the main methodologies used is *failure mode and effects analysis* (FMEA) for the characterization of system critical components. Liu et al. [5] collect a sample of 75 papers on FMEA to emphasize its strengths and weaknesses in many practical applications.

FMEA is a good driver for making decisions – despite the fact that it is a discretionary approach. In particular, the output from this analysis is significant for planning maintenance activities. Arunraj and Maiti [6] apply decisional multi-criteria to manage maintenance actions by considering risk and cost as criteria. The authors suggest the use of the *analytic hierarchy process* (AHP) [7] to select the maintenance policy that represents the best compromise between the considered criteria. FMECA is an extension of FMEA that enables quantitative analyses.

The aim of the present research is to propose a combined approach based on an integration of FMECA and TOPSIS [8]. The latter is suggested to obtain a critical component ranking and is applied in its fuzzy version (FTOPSIS) [9]. Taking into account various criteria, the TOPSIS method easily enables obtaining a priority index for each component of the system. The priority index, characterizing each component, could represent a driver in the scheduling phase of maintenance activities.

The TOPSIS method has been explained and proposed in previous research with the aim of selecting the maintenance plan for a multi-component system [10]. In [10], a wide list of papers that suggest using the TOPSIS method in the maintenance field is reported.

The integration between tools for reliability analysis, such as FMEA and multi-criteria methods, has been suggested by Emovon et al. [11]. These authors prioritize the analyzed risk factors with the aim of making a detailed and realistic study of marine machinery systems by means of the VIKOR method [12].

As emphasized by Pei [13], the TOPSIS technique is also fairly flexible in a fuzzy environment in which linguistic variables are used to compute a risk index. As highlighted by Kutlu and Ekmekçioğlu [14], the subjective attribution of crisp indices might be misleading. For this reason, they propose a fuzzy multi-criteria approach to take into account subjective uncertainty. The authors suggest an integrated use of fuzzy-AHP (FAHP) [15] and FTOPSIS to determine: first of all, weights for risk factors; and to obtain, secondly, a classification of possible faults. This possibility is also shared by Rostamzadeh and Sofian [16], who suggest the use of FAHP and FTOPSIS to improve production system performances. The fuzzy approach has been largely considered in the risk assessment phase. Grassi et al. [17] present a multi-attribute model based on fuzzy logic to quantitatively calculate the risk of common activities in a generic industrial process.

The remainder of the paper is organized as follows. The next section describes FMECA. Section 3 describes the proposed approach, and the final section refers to a real case related to a street cleaning vehicle. Finally, the conclusions close the work.

2. Failure Modes, Effects and Criticality Analysis

FMECA is a development of the FMEA that, on the basis of CEI EN 60812 Standard [18] definition, represents a systematic procedure to identify all the potential failure modes that could involve the system and its main components, their causes, and the related effects on system performance. FMECA includes a quantitative evaluation of the three following risk parameters: namely, severity (*S*); occurrence (*O*); and detection (*D*). The first is an estimate of how strongly the effects of the failure will affect the system; the second considers the frequency of occurrence in a determined period of time; and the final parameter represents the probability of detecting the failure [18]. For each failure mode, the multiplication of parameters *O*, *S* and *D* leads to the risk priority number (*RPN*):

$$RPN = S \cdot O \cdot D \tag{1}$$

Each risk factor generally assumes a discrete value inside a certain range. Yang et al. [19] underline how, especially when multiple experts give different evaluations about the same failure mode, the use of the evidence theory [20] represents a valid support to manage the uncertainty that characterizes this type of evaluation. Carmignani [21] suggests the use of a fourth parameter to include in the RPN calculation. The author proposes taking into account the profitability – based on costs and possible profits after minimizing losses due to failures. Many authors [22] consider FMECA and the development of risk analysis as an essential part of maintenance management strategies. In particular, Vernez and Vuille [23] emphasize the good adaptability of the FMECA as a tool for analyzing complex macro-systems with different hierarchical levels. They support the use of the methodology for reliability optimization and identifying the main vulnerabilities.

The first step in FMECA is the description of the considered system and the construction of a hierarchical structure. To obtain an exhaustive description of a complex system, it is firstly necessary to acquire information about the reliability relations among the system components and to physically describe them, with their own order and position (defining system boundaries and levels). It is clearly suggested excluding from the study those components that will not be evaluated nor taken into consideration in the analysis. The functional relationships between components can be finally formalized in a system block diagram. Moreover, it is necessary to define all the possible failure modes for each component, detect the failure causes, and define both the local and the system level failure effects. All the results must be summarized in worksheets that support the analyst in formalizing the phase of risk evaluation.

3. FTOPSIS to support FMECA analysis

TOPSIS is a *multiple criteria decision making* (MCDM) methodology that was originally developed by Hwang and Yoon [8].

The technique permits flexible applications in differing contexts and can be easily adapted to satisfy specific needs. Hu et al. [24] propose an algorithm, developed on the basis of the TOPSIS method by considering various scenarios. The TOPSIS method can be applied by a single analyst or decision maker and, as shown by Lourenzutti and Krohling [25], by a decision-making group. The authors have dealt with the flexibility of this multi-criteria technique, especially in a dynamic context of investment projects, design development, or supplier management. The literature offers examples of TOPSIS applications to manage the uncertainty that characterizes input data or imprecise information [26].

The use of fuzzy TOPSIS is proposed in the present paper. This extension, originally developed by Chen [9], is believed to be more suitable in real situations affected by data uncertainty. To apply FTOPSIS, it is firstly necessary to consider as input data the matrix:

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \tag{2}$$

in which the generic component $\tilde{x}_{ij}$ is a fuzzy number that represents the score of alternative i under criterion j. In particular, the fuzzy numbers used here are triangular fuzzy (TFN)

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}), \tag{3}$$

or even trapezoidal (TrFN) [27], whose membership functions belong to the interval [0,1].

The matrix $\tilde{X}$ must be normalized with relation to different criteria, and the obtained result is a matrix called $\tilde{Z}$:

$$\tilde{Z} = \begin{bmatrix} \tilde{z}_{11} & \cdots & \tilde{z}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{z}_{m1} & \cdots & \tilde{z}_{mn} \end{bmatrix}, \tag{4}$$

where the components, considering here TFN, are obtained as follows:

$$\tilde{z}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right),\ j \in I', \tag{5}$$

$$\tilde{z}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right),\ j \in I'', \tag{6}$$

I' being the subset of criteria to be maximized and I'' the subset of criteria to be minimized. c_j^* and a_j^- are:

$$c_j^* = \max_i c_{ij} \ \text{ if } j \in I', \tag{7}$$

$$a_j^- = \min_i a_{ij} \ \text{ if } j \in I''. \tag{8}$$

The abovementioned normalization method is applied to preserve the property that the ranges of the normalized triangular fuzzy numbers belong to the range [0,1].

It is now possible to build the weighted and normalized matrix $\tilde{U}$ to consider the different weights of each criterion. Thus, the generic component $\tilde{u}_{ij}$ of the output matrix $\tilde{U}$, is calculated as:

$$\tilde{u}_{ij} = \tilde{z}_{ij} \cdot w_j, \tag{9}$$

in which w_j represents the weight of the generic criterion j.

Referring to the entries of matrix $\widetilde{U}$, we have to consider the fuzzy positive ideal solution (A^*) and the fuzzy negative ideal solution (A^-):

$$A^* = (\tilde{u}_1^*, \tilde{u}_2^*, \dots, \tilde{u}_n^*), \tag{10}$$

$$A^- = (\tilde{u}_1^-, \tilde{u}_2^-, \dots, \tilde{u}_n^-), \tag{11}$$

where $\tilde{u}_j^* = (0,0,0)$ and $\tilde{u}_j^- = (1,1,1)$, $j = 1 \dots n$, if the preference with respect to criterion j is decreasing, and on the contrary if ascending.

The basic concept on which the TOPSIS is founded is that the alternative to select is that which is characterized by a minimal distance from A^* and the greatest distance from A^-. On the basis of this concept, it is possible to rank the alternatives by calculating the distance of each from A^* and A^- by means of the vertex method [9]. According to this method, the distance $d(\tilde{m}, \tilde{n})$ between two triangular fuzzy numbers $\tilde{m} = (m_1, m_2, m_3)$ and $\tilde{n} = (n_1, n_2, n_3)$ is a crisp value determined as:

$$d(\tilde{m}, \tilde{n}) = \sqrt{\tfrac{1}{3}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]}. \tag{12}$$

Similarly, the distance between two generic trapezoidal fuzzy numbers [28] $\tilde{t} = (t_1, t_2, t_3, t_4)$ and $\tilde{r} = (r_1, r_2, r_3, r_4)$ is the following crisp value:

$$d(\tilde{t}, \tilde{r}) = \sqrt{\tfrac{1}{4}[(t_1 - r_1)^2 + (t_2 - r_2)^2 + (t_3 - r_3)^2 + (t_4 - r_4)^2]}. \tag{13}$$

By aggregating with respect the criteria for each alternative i, the distances from A^* and A^- can be calculated as:

$$d_i^* = \textstyle\sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}_j^*) \quad i = 1 \dots n, \tag{14}$$

$$d_i^- = \textstyle\sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}_j^-) \quad i = 1 \dots n. \tag{15}$$

To rank the alternatives, it is finally necessary to calculate the crisp closeness coefficient CC_i, based on (14) and (15):

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*} \ . \tag{16}$$

Thus, referring to the proposed analysis and, according to the value of CC_i, the ranking order of all failure modes can be determined.

The following case study shows how the use of FTOPSIS supports the FMECA analysis. The results of this analysis can be easily treated by means of the FTOPSIS method to obtain a risk classification regarding the failure modes of the components in the analyzed system.

4. Case study

The considered system is a vehicle used to provide a street cleaning service and the previously mentioned combined approach is proposed. The system has been described through the relative block diagram (Fig.1) shown in a collapsed form. A wide list of failure modes has been obtained by applying FMECA. In particular, each subsystem (1, 2, …, 5) is characterized by a number of possible failure modes (A, B, …, F). For instance, the ID 5.2.1.A in Table III indicates failure mode "A" (hydraulic engine fault) for component "5.2.1." (rear roller), and so on.

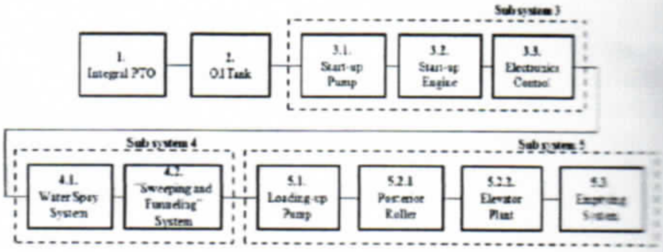

Figure1: System block diagram

The evaluation of each failure mode has been conducted on the basis of three criteria representing risk factors. Two are related to severity and the final one concerns frequency of occurrence. The two criteria related to severity are time and modality. They both refer to the execution of the maintenance activities related to specific faults and represent, respectively: the time of operation (expressed in hours); and the modality of the maintenance action execution (expressed by a quantitative scale of difficulty values). In detail, a maintenance action implies a lower level of difficulty if conducted in the same place where the failure occurred, and by an immediately available operator. Similarly, the maintenance action is medium-complex when it is necessary to ask for a specialized maintenance team; and finally, the action is complex if it has to be made in a repair shop (by also considering the transport time of the vehicle).

TABLE I. CONSIDERED CRITERIA FOR EVALUATION

Criteria	Description	w_j
C_1	Time of operation	0.4
C_2	Modality of execution	0.2
C_3	Frequency of occurence	0.4

The weights of these criteria have been assigned by a group of decision makers by applying the AHP technique (Table I). For reasons of space the related matrices of pairwise comparisons are not reported here. Table II shows the fuzzy scales [15] [26] used by the experts to evaluate the failure modes under the three criteria.

TABLE II. LINGUISTIC TERMS AND ASSOCIATED FUZZY NUMBERS

C_1	Fuzzy number		C_3	Fuzzy number
Very Low (VL)	$(0,0,\frac{1}{2},\frac{3}{2})$	TrFN	Improbable (I)	(0,0,1,3)
Low (L)	$(\frac{1}{2},\frac{3}{2},\frac{5}{2})$	TFN	Remote (R)	(1,3,5)
Medium (M)	$(\frac{3}{2},\frac{5}{2},\frac{7}{2})$	TFN	Occasional (O)	(3,5,7)
High (H)	$(\frac{5}{2},\frac{7}{2},\frac{9}{2})$	TFN	Probable (P)	(5,7,9)
Very High (VH)	$(\frac{7}{2},\frac{9}{2},5,5)$	TrFN	Frequent (F)	(7,9,10,10)

C_2	Fuzzy number	
Low Impact (LI)	(1,2,3)	TFN
Medium Impact (MI)	(2,3,4)	TFN
High Impact (HI)	(3,4,5)	TFN

The ranking of the failure modes obtained using FTOPSIS is shown in Table III.

TABLE III. RANKING OF FAILURE MODES

ID	Failure Modes	C_1	C_2	C_3	$CC_i\downarrow$
2A	Overheated oil	H	HI	P	0.935045
5.2.2D	Broken chain (elevator plant)	H	HI	P	0.935045
1B	Worn PTO bearings	VH	HI	O	0.929835
5.2.2C	Broken skid (elevator plant)	M	HI	P	0.924834
5.3A	Fault in support arm in the tank structure (emptying system)	H	HI	O	0.924834
5.3B	Slackened pivots or worn journal boxes in the tank structure (emptying system)	M	HI	P	0.924834
4.2C	Damaged brush or roller	H	MI	P	0.917395
4.1C	Fault in distribution system of the water pump	VH	MI	O	0.912216
3.3A	Fault in electrical system	VH	MI	O	0.907235
5.2.1D	Fault in support arm (rear roller)	H	MI	O	0.907235
5.2.1E	Slackened pivots or worn journal boxes (rear roller)	M	MI	P	0.907235
4.2E	Fault in electrical system	M	MI	O	0.897098
5.2.1B	Fault in actuator (rear roller)	M	MI	O	0.897098
1A	Broken PTO mechanism	VH	HI	R	0.887315
1C	Broken PTO universal joint shafts	VH	HI	R	0.887315
3.1A	Fault in distribution system (start-up pump)	VH	HI	R	0.887315
3.1B	Mechanical fault (start-up pump)	VH	HI	R	0.887315
3.2A	Stopped start-up engine	VH	HI	R	0.887315
3.2B	Mechanical fault (start-up engine)	VH	HI	R	0.887315
4.1B	Drilled water tank	M	HI	R	0.872398
5.3C	Overturning cylinder fault in the tank structure (emptying system)	M	HI	R	0.872398
5.3D	Broken or stopped releasing cylinder of the elevator plant	M	HI	R	0.872398
4.1D	Mechanical fault of the water pump	VH	MI	R	0.87007
2B	Insufficient oil level	L	MI	P	0.865172
2C	Clogged filters	L	MI	P	0.865172
4.1A	Empty water tank	L	MI	P	0.865172
4.1E	No working nozzles	L	MI	P	0.865172
4.1F	Clogged nozzles	L	MI	P	0.865172
4.2A	Fault distribution system in Pump I	H	MI	R	0.865172
4.2B	Mechanical fault in Pump I	H	MI	R	0.865172
5.2.1C	Worn bristles (rear roller)	L	MI	P	0.865172
1D	Fault general electrical system	L	MI	O	0.855222
4.2D	Fault hydraulic cylinders	L	MI	O	0.855222
5.1B	Mechanical fault (loading-up pump)	M	MI	R	0.855222
5.2.2A	Fault in Pump III (elevator plant)	M	MI	R	0.855222
5.1A	Fault in distribution system (loading-pump)	L	MI	R	0.8145
5.2.1A	Fault in hydraulic engine (rear roller)	L	MI	R	0.8145
5.2.2B	Fault in hydraulic engine (elevator plant)	L	MI	R	0.8145

5. Conclusions

The proposed combined approach starts from the use of FMECA as a reliability analysis and enables obtaining the ranking of failure modes using the FTOPSIS multi-criteria method. This enables the uncertainty that could affect the FMECA to be taken into account and, simultaneously, a consideration of quantitative and qualitative criteria. Furthermore, the proposed approach enables choosing criteria that highlight risk conditions with respect to the classical approach based on ranking the RPN index. Future developments could focus on assignment of the failure modes into risk classes on the basis of previously described criteria.

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