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DETERMINATION OF FAILURES PRIORITY BASED ON FMEA, FUZZY SETS, AND FUZZY LOGIC RULES

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Abstract. *In the automotive industry, the evaluation and analysis of failures are conducted by applying the conventional Failure Mode and Effect Analysis (FMEA). The technological, political, market, and other changes, as well as limited financial resources allocated for enhancement, require emerging models for failure analysis. In this research, the priority of failures is obtained by using the proposed fuzzy method based on fuzzy logic rules. All existing uncertainties in the examined problem are described by linguistic expressions which are modelled by using the fuzzy sets theory. The weights vector of risk factors is obtained by the fuzzy Best Worst Method. The priority of failures is determined by using fuzzy IF THAN rules. The obtained priority is compared with the priority of failures which is given by using conventional FMEA. The proposed model is tested on the FMEA report which came from one automotive company that operates in the Republic of Serbia.*

Key words: *Priority of failures, FMEA, fuzzy sets, fuzzy BWM, fuzzy logic*

1. INTRODUCTION

In order to ensure customer satisfaction, it is necessary to identify, evaluate and eliminate failures in the manufacturing process. The evaluation and determination of failure priorities are based on the Failure Mode and Effect Analysis – FMEA [13]. The FMEA team estimates the values of risk factors (RFs) by using the standard tables for the automotive industry also proposed by AIAG&VDA [2]. The risk priority number (RPN) is calculated by multiplying RFs. Liu et al. [10] stated that the traditional FMEA has moderate disadvantages. One of the main shortcomings is that severity is considered only from the aspect of quality. In the literature, there is many papers in which procedures for a more detailed analysis of severity have been developed with cost aspect [3, 5, 14]. The same problem is identified for safety as suggested by [4]. Komatina et al. [9] considered severity from three aspects: quality, cost, and importance of the product.

By applying conventional FMEA, all identified failures could be divided into two groups: obligatory and non-obligatory. These obligatory failures must be eliminated regardless of the cost of their elimination. A newer version of the handbook [2] implies that the priority of failures is determined by respecting the Action priority (AP). In this way, all failures are divided into three categories: failures with low importance, failure with medium importance, and failures with high importance. It can be considered that in this way another important shortcoming of conventional FMEA has been eliminated - that RFs do not have equal weights. The disadvantage of AP is that the weights of RFs are determined based on the experience of practice which can be concluded to be highly burdened by the subjective assessments of FMEA teams.

The motivation for this research comes from the fact that it is necessary to develop a model based on fuzzy logic rules that are easily understood by practitioners whose application is simple. In this way, the obtained priority of failures is significantly less burdened by the subjective assessment of the FMEA team.

Respecting the nature of human thinking, it can be said that FMEA team can more easily and accurately express their estimates using natural language words than precise numbers. The development of the fuzzy sets theory [15] allows vagueness to be represented fairly quantitatively. Many authors suggest using the triangular fuzzy numbers (TFNs) and trapezoidal (TrFNs).

There are a number of papers that can be found in the literature in which estimates of the relative importance of different items stand on pair-wise comparison matrices by analogy [11, 12]. The weights vector is obtained by using a stated nonlinear optimization model. There are numerous advantages of BWM compared to AHP [1]: i) it needs less pairwise comparison data compared to a full pairwise comparison matrix, and ii) the results generated by BWM are more consistent than those of AHP. Many authors suggest that in conditions of uncertainty, BWM should be expanded with fuzzy sets theory [6,7].

Determining the level of risk in different domains is based on fuzzy logic rules [8].

The objective is to evaluate and choose failures that have the highest priority for the FMEA team. This aim may be interpreted as (1) modeling of the existing uncertainties are performed by fuzzy numbers, (2) weight vector is obtained by FBWM, and (3) priority of failures is given by fuzzy IF-THAN rules. The proposed model is understandable and can be easily applied in practice.

The paper is organized in the following way: in Section 2 there is a problem statement. The proposed algorithm is presented in Section 3. The proposed model is illustrated by real-life data as presented in Section 4. Conclusion and discussion are given in Section 5.

2. THE MODEL STATEMENT

In this section, the problem of prioritizing the manufacturing process in automotive companies is presented.

2.1 Notation

In order to better understand the model, a notation was introduced, which is presented below.

I	Total number of identified failures
i	Index of failure
K	Total number of RFs
k	Index of RF
$\tilde{a}_{Bk}$	TFN describing fuzzy the preference of the best RF over the rest RFs
$\tilde{a}_{Wk}$	TFN describing fuzzy the preference of the worst RF over the rest RFs
$\tilde{\omega}_k$	TFN describing fuzzy weight of RF k, $k = 1,..,K$
v_{ik}	Crisp values of RF $k, k = 1,..,K$ for failure $i, i = 1,...,I$
$\tilde{x}_{ik}$	TFN describing the weighted values of RFs
$\tilde{z}_i$	TFN describing the fuzzy risk factor priority
z_i	The representative scalar of TFN $\tilde{z}_i$

2.2 Modelling of uncertainties

The considered RFs have different relative importance which can be considered unchangeable during the considered period of time. The relative importance of RFs are assessed by using the four linguistic expressions corresponding to TFNs:

Equal important (I1) - $(1,1,1)$, *Low important (I2)* - $(1,2,7)$, *Moderate important (I3)* - $(2,5,8)$, and *Very important (I4)* - $(3,8,9)$.

The proposed priority regions represent the baseline for priority assessment which means that the obtained priority index values will fit into one of them. The priority regions can be modeled by one of the three predetermined linguistic terms which are modeled by TrFNs:

Low priority (L) - $(0.3, 0.3, 0.7, 3)$, *Moderate priority (M)* - $(0.5, 1, 2, 2.5)$, and *High priority (H)* - $(1, 3, 3.3, 3.3)$.

The domains of these TFNs are defined in the interval [1-9] by analogy [12]. The value 1, i.e. 9 denotes that the relative importance of the RF k to k' is equal, i.e., extremely higher, respectively. The TrFNs domains are defined at interval intervals [0.3-3.3]. The value of 0.3 and 3.3 means that all RFs have the least impact on the priority of failure respecting their weights, simultaneously.

Since the overlap from one TFNs and TrFNs to the other is very high, it obviously indicates that there is a lack of knowledge about the relative importance of RFs and priority regions. These values may be changed and adjusted according to the specific needs of the treated enterprises from the automotive industry.

3. THE PROPOSED ALGORITHM

This section presents the proposed Algorithm which is realized through the following steps.

Step 1. The FMEA team should assess the relative importance of RFs by consensus. The resulting fuzzy best-to-others vector (FBO), $\tilde{\tilde{A}}_B$ and fuzzy other-to-worst vector (FOW), $\tilde{\tilde{A}}_W$ would be presented as:

$$\tilde{A}_B = (\tilde{a}_{B1}, \dots, \tilde{a}_{Bk}, \dots, \tilde{a}_{BK})$$

$$\tilde{A}_W = (\tilde{a}_{W1}, \dots, \tilde{a}_{Wk}, \dots, \tilde{a}_{WK})^T$$

Step 2. Find the optimal weights of RFs, $(\widetilde{\omega}_1^*, \dots, \widetilde{\omega}_k^*, \dots, \widetilde{\omega}_K^*)$, by using the following mathematical model which is constructed by [6,7]:

The objective function

$$min \max_{1=1,..,K} \left\{ \left| \frac{\widetilde{\omega}_B}{\widetilde{\omega}_k} - \tilde{a}_{Bk} \right|, \left| \frac{\widetilde{\omega}_k}{\widetilde{\omega}_W} - \tilde{a}_{kW} \right| \right\}$$

Subject to

$$\text{defuzz} \left(\sum_{k=1}^{K} \widetilde{\omega}_k = 1 \right)$$

$$l_k \leq m_k \leq u_k \qquad k = 1, \dots, K$$

$$l_k \geq 0 \qquad k = 1,..,K$$

Step 3. The presented mathematical model could be transformed into a linear programming model for minimizing the absolute gap as $\left((\varphi^*, \varphi^*, \varphi^*; 1) \right)$.

The objective function

$$\min \varphi^*$$

Subject to

$$|l^* - l_{Bk} \cdot l| \leq \varphi^* \qquad |m^* - m_{Bk} \cdot m_k| \leq \varphi^* \qquad |u^* - u_{Bk} \cdot u_k| \leq \varphi^*$$

$$|l_k - l_{Wk} \cdot l'| \leq \varphi^* \qquad |m_k - m_{Wk} \cdot m'| \leq \varphi^* \qquad |u_k - u_{Wk} \cdot u'| \leq \varphi^*$$

$$l_k \geq 0 \qquad l_k \leq m_k \leq u_k \qquad \frac{1}{6} \left(\sum_{k=1,..,K} (l_k + 4 \cdot m_k + u_k) \right) = 1$$

The weights vector of RFs, $(\widetilde{\omega}_1, \dots, \widetilde{\omega}_k, \dots \widetilde{\omega}_K)$ is given by solving the model.

Step 4. Determine the weighted value of RF k, for failure $i, i = 1, \dots, I$:

$$\tilde{x}_{ik} = v_{ik} \cdot \widetilde{\omega}_k$$

Step 5. Determine the fuzzy priority index, $\tilde{z}_i$:

$$\tilde{z}_i = (\cup \ \tilde{x}_{ik})$$

and the representative scalar of TFN, $\tilde{z}_i$ is z_i^*:

$$z_i^* = defuzz \ \tilde{z}_i$$

Step 6. Priority of failure $I, i = 1, \dots, I$ is determined according to the rule:

IF the value of "priority index" equals z^*, THEN the priority level is described by pre-defined linguistic expression.

Step 7. Compare the obtained solution from the previous step (Step 6) and the priority obtained by applying RPN and AP.

4. CASE STUDY

This paper discusses the FMEA report from the company that exists within the automotive supply chain. The FMEA report presented in this paper comes from the manufacturing process of this company. According to the proposed Algorithm (Step 1) the FBO and FOW are stated:

$$\tilde{A}_B = (I1, I3, I4) \qquad \tilde{A}_W = (I4, I2, I1)^T$$

The weights vector of RFs is obtained (Step 2 to Step 3):

$\widetilde{\omega}_1 = (0,0.79,0.86)$, $\widetilde{\omega}_2 = (0,0.14,0.14)$, and $\widetilde{\omega}_3 = (0,0.06,0.06)$.

The proposed procedure (Step 4) is illustrated for failure (i=1):

$\tilde{x}_{11} = 6 \cdot (0,0.79,0.86) = (0,4.74,5.15)$, $\tilde{x}_{12} = 2 \cdot (0,0.14,0.14) = (0,0.28,0.28)$ and

$\tilde{x}_{13} = 7 \cdot (0,0.06,0.06) = (0,0.42,0.42)$

Priority of failure $(i = 1)$ is given by applying the procedure (Step 6 of the proposed Algorithm):

$\mu_L(z = 1.813) = 0.495$, $\mu_M(z = 1.813) = 1$, and $\mu_H(z = 1.813)$ =0.406.

$$\max(0.495; 1; 0.406) = 1$$

The failure $(i = 1)$ has the medium priority.

The priorities of other failures from the FMEA report were calculated in a similar way. The priority obtained using RPN and AP is shown in Table 1.

Based on the obtained results, it is clearly concluded that the priority of failures is different when different approaches are used. It is interesting to note that almost all failures that are marked as obligatory have the highest priority even when the proposed model is used. There is a significant difference in the priority of failures obtained with the AP and the proposed model.

5. CONCLUSION

This paper presents a new model for determining the priorities of failures in the manufacturing process. Based on the obtained results, the FMEA team may define appropriate management activities that should lead to the elimination of failures which is further propagated to the long-term sustainability of the company.

The main contributions of the proposed model are: 1) The existing uncertainties are described by pre-defined linguistic terms which are modelled by fuzzy numbers; 2) The weights vector is conducted by using FBWM; 3) The calculating of RPN is achieved by rules of the fuzzy algebra; 4) Determination of priorities is based on the fuzzy IF THAN rules, and 5) All the changes, as with the changes in the number of failures as well as the number of RFs can be easily incorporated into the model.

The general limitations related to the proposed model are the fuzzy rating of the relative importance of RFs as well as the determination of the domains of priority depending on the knowledge and experience of the FMEA team.

Future research should include the development of a software solution that would enable the user-friendly of the proposed model.

Table 1. Priority of considered failures

Failure	Priority based on RPN	Priority based on AP	Priority based on the proposed model	Failure	Priority based on RPN	Priority based on AP	Priority based on the proposed model
i=1	7-8	L	M	i=14	obligatory	M	H
i=2	9	L	M	i=15	obligatory	M	H
i=3	3-5	L	H	i=16	7-8	L	M
i=4	obligatory	M	H	i=17	obligatory	M	M
i=5	obligatory	M	H	i=18	1-2	M	H
i=6	6	M	M	i=19	obligatory	H	H
i=7	obligatory	M	M	i=20	3-5	L	H
i=8	1-2	M	H	i=21	7	L	M
i=9	12	L	M	i=22	13	L	L
i=10	14-16	L	L	i=23	10-11	L	M
i=11	14-16	L	L	i=24	10-11	L	M
i=12	14-16	L	L	i=25	obligatory	L	M
i=13	3-5	L	H				

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