A new approach for evaluation of risk priorities of failure modes in FMEA

A new approach for evaluation of risk priorities of failure modes in FMEA

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This paper presents a method for carrying out the calculus of the risk priority of failures in Failure Mode and Effect Analysis (FMEA). The novelty of the method consists of new management of data provided by the design team, normally given on qualitative scales, without necessitating an arbitrary and artificial numerical conversion. The practical effects of these issues are shown in an application example.

1. Preliminary considerations

Since its introduction as a support tool for designers, FMEA (Failure Mode and Effect Analysis) has been extensively used in a wide range of contexts (Stamatis 1995, Hatty and Owens 1995, Bowles 1998). The great number of papers published in various technological and service areas bear witness to this interest (Hatty and Owens 1995, Wirth *et al.* 1996).

Designers' interest in FMEA is due to its capacity to perceive two very important aspects:

- the capability of stimulating the application of the continuous improvement concept in design (Franceschini and Rossetto 1995b);
- the possibility of methodical documenting of the design evolution.

FMEA is a reliability tool, which requires identifying failure modes of a specific product or system, their frequency and potential causes. It is normally applied by an interfunctional work team, with the right know-how to analyse the whole product life cycle.

As a result of its application, it allows 'quantifying' how 'dangerous' a failure mode is, and also provides a rank of risk priorities of failure modes and a list of corrective actions to remove them.

A typical form used for FMEA development is illustrated in table 1. It shows a list of items that identify:

- the system or component part
- the potential failure mode
- the potential effect of failure
- the severity index (S)

Part name and part function	Potential failure mode	Potential effect(s) of failure	*S*	Potential cause(s) of failure	*O*	Design verification	*D*	*RPN*
Motor: provide mechanical power to fans; position fans within shroud	Fan vibration from imbalance and axial TIR	Audible noise vibration; increased motor wear	5	Fasn centre of gravity off axis of rotation; axial TIR causes 2-plane imbalance	5	Design lightwieght fan with min. band mass; part thickness to favour uniform mould flow. DV tests on vehicles to assess sensitivity to vibration inputs	4	100
Motor: provide mechanical power to fans; position fans within shroud	Motor burnout bearing or brush failure	Loss of cooling and A/C function	5	Overheating, lack of air circulation	2	Vent holes in motor case; fins in fan hub pull air through ES, durability tests	5	50
Motor: provide mechanical power to fans; position fans within shroud	Misassemble to shroud, off centre or crooked	Loss of cooling function	7	Fan contact shroud, noise or motor-burn-out	2	Design for easy assembly, accurate positioning in shroud	3	42
Motor: provide mechanical power to fans; position fans within shroud	Assemble at $\pm 12^\circ$ off-nominal angle, motor wire in wrong location	No-build condition in assy plant	6	Symetrical spacing of screw holes; non-unique mounting interfaces	6	Power motion motor has unique mounting configuration. Visual inspection during assembly	3	108

Table 1. Application of FMEA to the design of a cooling fan assembly (Stamatis 1995).

- the potential cause of failure
- the frequency of occurrence index (O)
- the design verification actions
- the detectability index (D)
- the Risk Priority Number (RPN).

The characteristic failure mode indexes are expressed on ordinal *qualitative scales* (Fraser 1994, Franceschini and Rossetto 1997) identifying the various levels of 'dangerous' situations. Tables 2, 3 and 4 show the qualitative scales mostly used for the severity, the detectability and the occurrence indexes (Stamatis 1995). It is assumed that all index scales have the same number of scale levels.

For a generic design, after the identification of failure modes, effects and causes of a possible occurrence, the *Risk Priority Number* (RPN) is calculated. RPN is an index that expresses the risk level priority associated with each failure mode.

In the traditional FMEA approach, the RPN index is determined by calculating the product of the three indexes: severity, frequency and detection:

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

In the RPN calculation, the assigned values on the three index qualitative scales are interpreted as being numbers. 'Information initially gathered on the qualitative scales' is therefore *arbitrarily* interpreted and utilized on a quantitative scale with different properties from the first one.

Level		Criteria
No	1	No effect.
Very slight	2	Customer not annoyed. Very slight effect on product or system performance.
Slight	3	Customer slightly annoyed. Slight effect on product or system performance.
Minor	4	Customer experiences minor nuisance. Minor effect on product or system performance.
Moderate	5	Customer experiences some dissatisfaction. Moderate effect on product or system performance.
Significant	6	Customer experiences discomfort. Product performance degraded, but operable and safe. Partial failure, but operable.
Major	7	Customer dissatisfied. Product performance severely affected but functionable and safe. System impaired.
Extreme	8	Customer very dissatisfied. Product inoperable but safe. System inoperable.
Serious	9	Potential hazardous effect. Able to stop product without mishap—time dependent failure. Compliance with government regulation is in jeopardy.
Hazardous	10	Hazardous effect. Safety related—sudden failure. Non-compliance with government regulation.

Table 2. Qualitative scale for the severity index (S) (Stamatis 1995).

Effect	Level	Criteria
Almost never	1	Failure unlikely. History shows no failure.
Remote	2	Rare number of failures likely.
Vert slight	3	Very few failures likely.
Slight	4	Few failures likely.
Low	5	Occasional number of failures likely.
Medium	6	Medium number of failures likely.
Moderately high	7	Moderately high number of failures likely.
High	8	High number of failures likely.
Very high	9	Very high number of failures likely.
Almost certain	10	Failure almost certain. History of failures exists from previous or similar designs.

Table 3. Qualitative scale for the occurrence index (O) (Stamatis 1995).

Effect	Level	Criteria
Almost certain	1	Proven detection methods available in concept stage.
Very high	2	Proven computer analysis available in early design stage.
High	3	Simulation and/or modelling in early stage.
Moderately high	4	Tests on early prototype system elements.
Medium	5	Tests on preproduction system components.
Low	6	Tests on similar system components.
Slight	7	Tests on product with prototypes with system components installed.
Very slight	8	Proving durability tests on products with system components installed.
Remote	9	Only unproven or unreliable technique(s) available.
Almost imposible	10	No known techniques available.

Table 4. Qualitative scale for the detectability index (D) (Stamatis 1995).

In other words, the original ordinal scale is transformed in a new cardinal scale characterized by a metric and by the integer number composition properties.

The RPN is thus defined on a rather special scale, which, moreover, does not completely cover the range $[1, 1000]$ of the integers because there are, for example, some 'holes' corresponding to prime numbers contained in the range itself.

This arbitrary 'promotion' of the scale properties brings about a series of problems in the RPN interpretation. In more detail, the data numbering involves:

- the definition of the RPN on a formally wider scale than that of the three component indexes, which generates a fictitious increase of its resolution;

- the assumption that the scales of the three S, O and D indexes have the same metric and that the same danger level corresponds to the same values on different index scales;
- the assumption that the three failure mode indexes are all equally important;
- the possibility of identifying, with the same RPN, situations characterized by different danger index levels. For example, the condition assigning to (S, O, D) indexes the values (8, 1, 1) is considered at the same level as (2, 2, 2). Both situations determine an $RPN = 8$. But is this statement legitimate?

The numeric data interpretation brings about the simplification of the RPN calculation; however, it also increases the risk of moving its meaning away from the logic of the design team that supplied the figures.

The numbering—acknowledging 'metrological properties' higher than actually possessed by collected information—can therefore cause a 'distortion' effect, which can partially or completely distort the contents (Franceschini and Rossetto 1995a, 1998).

Other methods have been proposed for the RPN calculation in the literature (Bowles and Pelaez 1995, Goossens and Cooke 1997). However, they do not remove some of the complexities illustrated during the discussion. In particular, these methods are quite complex to manage and require the definition of special functions and/or a know-how that is not always available to designers. These issues stimulated the idea of setting up an alternative method to the traditional one. This method is able to solve some of the questions raised and, in particular, the need to introduce non-existing properties to estimate the RPN index. It also allows the design team to implement flexible strategies to detect the most dangerous failure modes.

The method also provides the possibility of considering the difference in importance of the characteristic indexes, so avoiding a further work burden for designers.

At the end of the discussion, an example of the new approach together with a comparison with the traditional procedure will be provided.

2. The method

The main aim of defining failure mode priorities is to draw the designer's attention towards the most dangerous failure modes for the product. For this to be an important effort improving the design quality, it must not alter the content of the information supplied by the design team during the analysis.

The proposed method is able to deal with information expressed on an ordered qualitative scale with no need to resort to an artificial numerical conversion of the scale. It can be classified within the class of ME-MCDM techniques (Multi Expert—Multiple Criteria Decision Making) (Yager 1993).

The use of qualitative scales raises a few issues for data processing. For example, in using numeric scales, the difference operation between two scale elements is defined, but this does not happen for qualitative scales, which have ordinal properties only.

The method is inspired by the work of Bellman and Zadeh, lately 'enriched' by Yager, for the solution of multi-criteria decision-making problems (Bellman and Zadeh 1970, 1975, 1976, Yager 1981, Yager and Filev 1994). In fact, FMEA can be considered as a decision-making support tool for designers. The decision consists of defining the order to analyse (from a design point of view) the failure mode effects of the considered product.

Characteristic indexes can be interpreted as evaluation criteria g_j (with $j = 1, \ldots, n$), while failure modes as the alternatives a_i (with $i = 1, \ldots, m$) to be selected.

The method considers each decision-making criterion (characteristic index) as a 'fuzzy' subset over the set of alternatives to be selected.

The grade of membership of alternative a_i in g_j indicates the degree to which a_i satisfies the criterion specified.

The model suggests a two-step procedure.

(i) Aggregation of evaluations expressed on each criterion for a given alternative (a_i)

$$RPC(a_i) = \underset{j}{\mathrm{Min}}\ [\mathrm{Max}\{\mathrm{Neg}(I(g_i)), g_j(a_i)\}, \tag{2}$$

where

$RPC(a_i)$	is the Risk Priority Code for the failure mode a_i.
$I(g_j)$	is the importance associated with each criterion g_j.
$\mathrm{Neg}(I(g_j))$	is the negation of the importances assigned to each decision-making criterion.

The negation of an s-point ordinal scale is calculated as follows (Yager 1981, 1993):

$$\mathrm{Neg}(L_i) = L_{z-i+1}, \tag{3}$$

where L_i is the ith level of the scale.

(ii) Determination of the failure mode with the maximum risk priority code (a^*)

$$RPC(a^*) = \underset{a_i \neq A}{\mathrm{Max}}\ \{RPC(a_i)\}, \tag{4}$$

where

A	is the set of failure modes.
$RPC(a_i)$	is defined on a new 10-point ordinal scale as those values utilized for expressing index evaluations.

If two or more failure modes have the same risk priority code we may obtain a more detailed selection considering the indicator $T(a_i) = DimA(a_i)$, where the operator $DimA(a_i)$ gives the number of elements contained in the set $A(a_i)$, and $A(a_i) = \{g_j(a_i) | g_j(a_i) > RPC(a^*)\}$. This term represents a second-step investigation for establishing a measure of the dispersion of criteria, related to a specific failure mode, around the RPC index. It gives an estimation of how many important criteria with high evaluations, compared with the calculated RPC, are present in the evaluation of each failure mode.

It is assumed that the importance associated with each evaluation criterion is defined on a 10-point ordinal scale similar to those used for index scales. It is also assumed that the same danger level corresponds to the same ordinal level on the different scales. Table 5 shows the correspondence map between the severity, occurrence and detectability indexes and their related importances. If the four scales do not have the same number of levels the mappings can become more complex.

Level	S Index	O Index	D Index	$I(S, O, D)$
L_1	No	Almost never	Almost certain	No
L_2	Very slight	Remote	Very high	Very low
L_3	Slight	Very slight	High	Low
L_4	Minor	Slight	Moderate high	Minor
L_5	Moderate	Low	Medium	Moderate
L_6	Significant	Medium	Low	Significant
L_7	Major	Moderately high	Slight	Major
L_8	Extreme	High	Very slight	High
L_9	Serious	Very high	Remote	Very high
L_{10}	Hazardous	Almost certain	Almost impossible	Absolute

Table 5. Correspondence map between severity, occurrence and detectability indexes and the qualitative scale for the importance associated with each evaluation criterion.

From equation (2) we note that the *Min* operation selects the smallest of its arguments. If all arguments are high they do not affect the min operation. Consider a criterion that has little importance, it will get an importance rating L_k that is low on the scale. When we take the negation of this score we get something high. When we take the *Max* of the importance criteria with the evaluation $g_j(a_i)$ we still get a high score. Thus, we see that low-importance criteria have little effect on the overall 'score'.

It can be shown that the formulation suggested in equation (2) satisfies the properties of Pareto optimality, independence to irrelevant alternatives, positive association of individual scores with overall score and symmetry (Yager 1981, 1993).

An essential feature of this approach is that we have no need to use numeric values and force undue precision on the design team experts.

We note that, in equation (2), we are implicitly assuming a logic to satisfy all characteristics that are important. The term $\text{Max}\{\text{Neg}(I(g_j)), g_j\}$ indicates a value for a given criterion to the statement 'if the criterion is important, then it has a high score'.

Equation (4) allows the selection of the failure mode with the maximum risk priority code. The rationale of the procedure is to consider the most dangerous failure modes to be those with the highest evaluations on the most important criteria. When two or more failure modes have the same ranking we provide a more detailed selection with the $T(a_i)$ index. $T(a_i)$ defines, for each failure mode, the cardinality of the total number of 'equivalent' risk levels associated with all criteria.

The traditional FMEA is not able to manage situations in which characteristic indexes have different importances. Some authors (Raheja 1991, De Risi 1996) suggest that an appropriate strategy is to analyse all failure modes that are above some specified threshold *RPN* or above some severity threshold. For instance, a design team might set a policy where all failure modes whose severity is higher than 9 will be analysed in addition to those failure modes whose *RPN* is above 500. This approach recognizes the need to differentiate the relative importance of the severity, occurrence and detection indexes, but proposes a rigid scheme in which the severity index is the most important.

In some particular contexts it might be necessary to change the order of priority among indexes or to change the logic of their analysis. The proposed method overcomes these constraints. It allows a more flexible structure for combining the index importances, and the possibility of defining different technical logics of analysis. If we change, in equation (2), the composition of the operators and the 'tie-ranking' rule, the design team may build models able to express logics of synthesis different from that proposed. For example, we might define RPC as $RPC(a_i) = \mathrm{Max}_j\{\mathrm{Min}[(I(g_j), g_j(a_i)]\}$, which represents a new logic in which the most dangerous failure mode is that with the highest evaluation on the most important criterion.

An application example may better explain the method.

3. An application example

Let us consider the example of a design of a cooling fan assembly (see table 1). Let us analyse four different situations.

(a) All characteristic indexes have the same max importance (L_{10}). This condition is very similar to the 'traditional' FMEA, where all the indexes have the same importance.

$$I(S) = L_{10}; \quad I(O) = L_{10}; \quad I(D) = L_{10}.$$

Calling a_1, a_2, a_3 and a_4 the four failure modes, the aggregated RPC index calculation is performed as indicated by equation (2).

According to equation (3), the negations of a 10-point ordinal scale are:

$$\begin{aligned}
&\mathrm{Neg}(L_1) = L_{10}; && \mathrm{Neg}(L_6) = L_5;\\
&\mathrm{Neg}(L_2) = L_9; && \mathrm{Neg}(L_7) = L_4;\\
&\mathrm{Neg}(L_3) = L_8; && \mathrm{Neg}(L_8) = L_3;\\
&\mathrm{Neg}(L_4) = L_7; && \mathrm{Neg}(L_9) = L_2;\\
&\mathrm{Neg}(L_5) = L_6; && \mathrm{Neg}(L_{10}) = L_1.
\end{aligned}$$

Now it is possible to calculate the RPC for the four failure modes (see column six of table 6):

$$\begin{aligned}
RPC(a_1) &= \mathrm{Min}_j[\mathrm{Max}\{\mathrm{Neg}(I(g_j)), g_j(a_1)\}]\\
&= \mathrm{Min}\{\mathrm{Max}[\mathrm{Neg}(L_{10}), L_5],\ \mathrm{Max}[\mathrm{Neg}(L_{10}), L_5],\\
&\mathrm{Max}[\mathrm{Neg}(L_{10}), L_4]\} = \mathrm{Min}\{\mathrm{Max}[L_1, L_5], \mathrm{Max}[L_1, L_5],\\
&\mathrm{Max}[L_1, L_4]\} = \mathrm{Min}\{L_5, L_5, L_4\} = L_4\\
RPC(a_2) &= \mathrm{Min}_j[\mathrm{Max}\{\mathrm{Neg}(I(g_j)), g_j(a_2)\}] = L_2\\
RPC(a_3) &= \mathrm{Min}_j[\mathrm{Max}\{\mathrm{Neg}(I(g_j)), g_j(a_3)\}] = L_2\\
RPC(a_4) &= \mathrm{Min}_j[\mathrm{Max}\{\mathrm{Neg}(I(g_j)), g_j(a_4)\}] = L_3.
\end{aligned}$$

Potential failure mode	S	O	D	RPN	RPC [Case (a)] $I(S)= L_{10}$ $I(O) = L_{10}$ $I(D) = L_{10}$	RPC [Case (b)] $I(S)= L_{10}$ $I(O) = L_8$ $I(D) = L_6$	RPC [Case (c)] $I(S)= L_{10}$ $I(O) = L_5$ $I(D) = L_1$	RPC [Case (d)] $I(S)= L_1$ $I(O) = L_5$ $I(D) = L_{10}$
a_1	5	5	4	100	L_4	L_5	L_5	L_4
a_2	5	2	5	50	L_2	L_3	L_5	L_5
a_3	7	2	3	42	L_2	L_3	L_6(*)	L_3
a_4	6	6	3	108	L_3	L_5(*)	L_6	L_3

Table 6. Calculation of *RPN* and *RPC* indexes for the design of a cooling fan assembly (Stamatis 1995). $I(S)$, $I(O)$, $I(D)$ are the importances associated with each index. *RPC* is calculated for four different situations: (a), (b), (c), (d). When two or more failure modes have the same *RPC* index, the symbol (*) highlights the most dangerous.

The maximum priority value is:

$$RPC(a^*) = \underset{a_i \in A}{\text{Max}} \; [RPC(a_1), RPC(a_2), RPC(a_3), RPC(a_4),]$$
$$= RPC(a_1) = L_4$$

and therefore the most dangerous failure mode is a_1.

(b) In some application contexts, it can be useful to define a different level of importance for the three *S*, *O* and *D* indexes. In this case we cannot use the traditional *RPN* approach.

If $I(S) = L_{10}; I(O) = L_8; I(D) = L_6$.

The *RPC* for the four failure modes (see column seven of table 6) are:

$$RPC(a_1) = \underset{j}{\text{Min}}[\text{Max}\{\text{Neg}(i(g_j)), g_j(a_1)\}] = L_5$$
$$RPC(a_2) = \underset{j}{\text{Min}}[\text{Max}\{\text{Neg}(i(g_j)), g_j(a_2)\}] = L_3$$
$$RPC(a_3) = \underset{j}{\text{Min}}[\text{Max}\{\text{Neg}(i(g_j)), g_j(a_3)\}] = L_3$$
$$RPC(a_4) = \underset{j}{\text{Min}}[\text{Max}\{\text{Neg}(i(g_j)), g_j(a_4)\}] = L_5.$$

The maximum priority value is:

$$RPC(a^*) = \underset{a_i \in A}{\text{Max}} \; [RPC(a_1), RPC(a_2), RPC(a_3), RPC(a_4)]$$
$$= RPC(a_1) = RPC(a_4) = L_5$$

In this case the most dangerous failure modes are a_1 and a_4.

With the aim of discriminating their relative ranking we calculate the indexes $T(a_1)$and $T(a_4)$:

$$A(a_1) = \{g_j(a_1)|g_j(a_1) > RPC(a^*)\} = \{g_j(a_1)|g_j(a_1) > L_5\} = \Phi$$
$$\Rightarrow \quad T(a_1) = Dim A(a_1) = Dim \Phi = 0$$
$$A(a_4) = \{g_j(a_4)|g_j(a_4) > RPC(a^*)\} = \{g_j(a_4)|g_j(a_4) > L_5\}$$
$$= \{g_1(a_4), g_2(a_4)\} = \{L_6, L_6\}$$
$$\Rightarrow \quad T(a_4) = Dim A(a_4) = 2.$$

Since $T(a_4) > T(a_1)$ then a_4 is the most dangerous failure mode.

(c) If $I(S) = L_{10}$; $I(O) = L_5$; $I(D) = L_1$

The *RPC* for the four failure modes (see column eight of table 6) are:

$$RPC(a_1) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_1)\}] = L_5$$
$$RPC(a_2) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_2)\}] = L_5$$
$$RPC(a_3) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_3)\}] = L_6$$
$$RPC(a_4) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_4)\}] = L_6.$$

The maximum priority value is:

$$RPC(a^*) = \underset{a_i \in A}{\text{Max}} [RPC(a_1), RPC(a_2), RPC(a_3), RPC(a_4),]$$
$$= RPC(a_3) = RPC(a_4) = L_6$$

and therefore the most dangerous failure modes are a_3 and a_4.

Since a_3 and a_4 have the same ranking, we calculate $T(a_3)$and $T(a_4)$:

$$T(a_3) = 1; \qquad T(a_4) = 0.$$

Being $T(a_3) > T(a_4)$, we conclude that a_3 is more dangerous than a_4.

(d) If $I(S) = L_1$; $I(O) = L_5$; $I(D) = L_{10}$.

The *RPC* for the four failure modes (see column nine of table 6) are:

$$RPC(a_1) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_1)\}] = L_4$$
$$RPC(a_2) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_2)\}] = L_5$$
$$RPC(a_3) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_3)\}] = L_3$$
$$RPC(a_4) = \underset{j}{\text{Min}}[\{\text{Max}\{\text{Neg}(I(g_j)), g_j(a_4)\}] = L_3.$$

The maximum priority value is:

$$RPC(a^*) = \underset{a_i \in A}{\text{Max}} [RPC(a_1), RPC(a_2), RPC(a_3), RPC(a_4),]$$
$$= RPC(a_2) = L_5.$$

The most dangerous failure mode is a_2.

Table 6 contains a synthesis of the *RPN* and *RPC* indexes for the example of table 1, using four sets of importances associated with each index.

Analysing the data contained in table 6 we can observe:

- lowering the importance attached to a particular index (for example, the detectability index), decreases its influence on the selected failure mode;
- the *RPC* index allows analysis of application cases in which we have a different importance for the three input indexes. This cannot be done by using the *RPN* index.
- if two or more failure modes have the same *RPC*, it is possible to perform a more detailed selection with the help of the $T(a_i)$ index. In such a way we can discriminate 'tie' situations in which the *RPN* gives the same result. Let us consider, for example, the two conditions assigning respectively the values (6, 1, 1) and (2, 3, 1) to (*S, O, D*) indexes;
- the mapping of failure modes on the *RPC* scale gives their relative importance only. The absolute value assumed is not important. So, for example, according to table 5, the level L_4 means that the corresponding failure mode has a priority lower than L_5 and higher than L_3;
- it must be noted that the proposed method allows for a more flexible structure for combining the indexes and defining different technical logics of analysis.

4. Conclusions

This paper introduces and discusses the application of a new method to calculate the risk priority level for the failure mode in FMEA. Data processing is performed by working exclusively on the ordinal features of qualitative scales used to collect information from designers. The method's processing simplicity is comparable with the *RPN* calculation.

The main novel elements of the proposed method are:

- it does not require any arbitrary and artificial scaling of collected information;
- it is able to deal with situations having different importance levels for the three failure mode component indexes;
- it is able to aggregate design team information, even if they are expressed on ordinal qualitative scales;
- it is easy to computerize.

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