MAFMA: multi-attribute failure mode analysis

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Abstract *The aim of this paper is to develop a new tool for reliability and failure mode analysis by integrating the conventional aspects of the popular failure mode and criticality analysis (FMECA) procedure with economic considerations. Here FMECA is approached as a multi-criteria decision making technique which integrates four different factors: chance of failure, chance of non-detection, severity, and expected cost. To aid the analyst to formulate an efficient and effective priority ranking of the possible causes of failure, the analytic hierarchy process technique is adopted. With this technique, factors and alternative causes of failure are arranged in a hierarchic structure and evaluated only through the use of a series of pairwise judgements. With this new approach to failure investigation, the critical FMECA problem concerning the (direct) evaluation of failure factors is also by-passed. The principles of the theory and an actual application in an Italian refrigerator manufacturing company are reported in the paper.*

Introduction

Considered as the last point in failure investigation (Holmberg and Folkeson, 1991), the failure mode, effects and criticality analysis (FMECA) technique (or FMEA, failure mode and effect analysis) is devoted to determining design reliability by considering potential causes of failure and their effects on the system under study (Countinho, 1964; Dillon, 1985; O'Connor, 1981). Briefly, FMECA is concerned with listing each potential failure mode of a (global) system and its effects on the listed subsystems. This bottom-up approach can be utilised at any level, from complete systems to components.

The main advantages of FMECA are:

- it is a visibility tool that can easily be understood and used;
- it is a systematic procedure which is arranged in a computer program based on a data base;
- it identifies weaknesses in the system design, focusing attention on a few components rather than on many;
- it is useful in design comparison.

Even though FMECA is probably the most popular tool for reliability and failure mode analysis, several problems are associated with its practical implementation. The timing of FMECA process at the design stage, the establishment of a well trained and balanced FMECA team, the co-ordination difficulties, are some of the problems listed by Teng and Ho (1996).

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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 economical aspects are neglected. In particular, frequently the maintenance staff would like to distinguish two different aspects of the terms "severity" (or "gravity"): the safety considerations from the expected cost due to failure. Consequently, different risk/failure analysis models based on more complete indices have developed. For example, Garrick (1988) considers indices including failure considerations about quality of the product, environmental safety, production loss, "domino effects", etc. De Vita *et al.* (1995) introduce a complete economical analysis of each possible failure including production loss cost, low quality cost, plant inactivity cost. Based on these contributions and the reliability of the operative unit considered, an average hourly cost is calculated and adopted as critical index of the failures. With the "facility risk review" (FRR) technique, Montague (1990) tries to quantify in a more precise way the economical gravity of a failure including considerations about the costs of defective products, corrective maintenance, etc. Economical considerations in FMECA are considered again in Bandelloni *et al.* (1999). The authors examine the case of a consulting company that has got some industrial systems' maintenance annual contract to manage, and they analyse the possibility of using economical evaluations in FMECA in order to define best maintenance strategies. Also Gilchrist (1993) discusses the absence of any cost evaluation of the failures in FMECA. In particular, the author develops an economic model to overcome the pitfalls of FMECA, which considers aspects such as the number of items produced (for example, per year) and the cost per fault. Ben-Daya and Raouf (1996) reconsider the problem underlined by Gilchrist, noting that the economic model addresses a problem which differs from the problem which FMECA is intended to address. Moreover, the new economic model completely ignores the important aspect of severity. For this reason the two authors propose a combination of the expected cost model and their new improved FMECA which overcomes another critical problem demonstrated by Gilchrist (i.e. the linear relation between score and associated failure probability).

Considering the different criteria that must be taken into account during failure analysis, and the practical difficulties in FMECA applications linked to a "direct" evaluation/quantification of the different factors, this paper proposes a multi-attribute approach based on the analytic hierarchy process (AHP) technique which integrates the aspects of the original FMECA and the economic considerations. Briefly, the AHP provides a framework to cope with multiple criteria situations involving intuitive, rational, qualitative and quantitative aspects. Following this procedure, a final ranking for every failure cause is evaluated. Here this new approach is called multi-attribute failure mode analysis (MAFMA).

FMECA theory and the criticality assessment problem

FMECA procedure involves several steps:

1. listing the subsystems and parts of the system (functional analysis);
2. listing and description of all failure modes for the part under consideration,
3. a criticality assessment is performed to measure the risk level for each fault in terms of factors such as the failure probability or the severity of failure;
4. ranking the faults with respect to the criticality assessment;
5. taking action on the high-risk problems;
6. checking the effectiveness of the action adopted and revised risk analysis.

Traditionally, the criticality evaluation is executed:

- calculating a criticality number (*CN*);
- developing a risk priority number (*RPN*).

The criticality number calculation is described in US MIL-STD-1629A "Procedures for performing a failure mode, effects and criticality analysis". The procedure consists of determining the failure-effect probability (β), the failure mode ratio (α), the part failure rate (λ), and its operating time (t), and using these values to compute a failure mode criticality number for each item failure mode *i* as:

$$CN_i = \alpha_i \cdot \beta_i \cdot \lambda_p \cdot t.$$

Criticality number technique is used mostly in the nuclear, aerospace, and chemical industries.

The RPN criticality calculation uses linguistic terms to rank the chance of the failure-mode occurrence S_f, the severity of its failure effect S, and the chance of the failure being undetected S_d on a numeric scale from 1 to 10. Well known "conversion" tables (see, for example, Ben-Daya and Raouf, 1996; Gilchrist, 1993; Pelaez and Bowles, 1994) report the typical basis for the linguistic judgement scales used to estimate the three quantities which are used to calculated the RPN value in the following manner:

$$RPN = S_f \times S_d \times S.$$

The RPN method is preferred mostly by the manufacturing industries such as automotive companies (Ford, 1988), domestic appliance firms (Zanussi, 1989), tire companies (Pirelli, 1988), etc.

Frequently, also in presence of data reported in the just cited conventional tables, for the experts of maintenance staff it is very difficult to give a "direct" and correct numerical evaluation of these (practically intangible) quantities. In fact, even if the two techniques are thought as "quantitative" approaches, they are really based on qualitative assessments, predicted failure rates, and other factors that are only guesses at the best. This problem makes them less precise than might at first appear to be.

To overcome this critical problem, fuzzy logic (FL) has been frequently proposed as a tool for directly manipulating the linguistic terms used in making the criticality assessment (Cayrac *et al.,* 1996; Kieselbach, 1997; Papic and Aronov, 1996; Pelaez and Bowles, 1994). Certainly FL represents an interesting and promising tool for directly manipulating the linguistic terms that maintenance personnel employs in making a criticality assessment for a FMECA. But some doubts remain in terms of an actual applicability in consideration of the difficulties in defining the (numerous) rules and membership functions required by this methodology.

An alternative and more traditional approach is proposed in Noè (1996) where guidelines and criteria for score assignment in risk evaluation are presented and applied in an important Italian tire production company.

A multi-attribute approach to the management of different aspects of failures

To help the analyst to formulate a more efficient and effective failure priority ranking, overcoming the FMECA problems described in the two previous sections, we assessed the recognised causes of failure from product reliability perspectives using the AHP technique.

The use of AHP is based on the following considerations:

- The necessity to integrate conventional aspects of FMECA based on probability of failure, chance of non-detection and severity with economic considerations. The different factors should be considered jointly and not in parallel, as proposed by Ben-Daya and Raouf (1996).
- The RPN evaluation based on a simple multiplication of the factors' scores is a debatable method. For example, it is not certain that all designers in every situation want to assign the same importance (i.e. weight) to each criterion.
- It is not easy to quantify the failure factors included in this analysis, even when adopting the scales based on linguistic judgements which represent a "tentative" proposal for the probability quantification but which lack a solid theoretical basis. For example, the public opinion damage generated by a product failure represents the main, but intangible, contribution to the final failure cost.
- Similarly to FMECA methodology, also AHP is well supported by powerful and efficient commercial software which easily permits the maintenance staff to execute complex and extended failure investigations. In particular, as shown below, important sensitivity analyses can be quickly conducted to verify the robustness of the obtained results.

The AHP (Saaty, 1980, 1990) is a powerful and flexible multi-criteria decision making tool for complex problems where both qualitative and quantitative aspects need to be considered. The AHP helps the analysts to organise the critical aspects of a problem into a hierarchical structure similar to a family tree. By reducing complex decisions to a series of simple comparisons and rankings, then synthesising the results, the AHP not only helps the analysts to arrive at the best decision, but also provides a clear rationale for the choices made.

The steps of the process are the following:

(1) Define decision criteria in the form of a hierarchy of objectives. The hierarchy is structured on different levels: from the top (i.e. the goal) through intermediate levels (criteria and sub-criteria on which subsequent levels depend) to the lowest level (i.e. the alternatives).

(2) Weight the criteria, sub-criteria and alternatives as a function of their importance for the corresponding element of the higher level. Both qualitative and quantitative criteria can be compared using informal judgements to derive weights and priorities. For qualitative criteria, AHP uses simple pairwise comparisons to determine weights and ratings so that the analyst can concentrate on just two factors at one time. In fact, AHP is based on the assumption that a decision maker can more easily place a comparative rather than an absolute value. The verbal judgements are then translated into a score via the use of discrete nine-point scales (Table I). After a judgement matrix has been developed, a priority vector to weight the elements of the matrix is calculated. Saaty (1980, 1990) demonstrates mathematically that the normalised eigenvector of the matrix is the best approach.

Taking into account quantifiable criteria, normalising the quantitative factor information AHP allows the decision maker to use it with other rankings.

(3) The AHP enables the analyst to evaluate the goodness of judgements with the inconsistency ratio I_R. Before determining an inconsistency measurement, it is necessary to introduce the consistency index CI of an

Judgement	Score
Equally	1
	2
Moderately	3
	4
Strongly	5
	6
Very strongly	7
	8
Extremely	9

Table I.
Judgement scores in AHP

$n \times n$ matrix (of judgements) defined by the ratio:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix. Then, $\mathrm{I_R}$ is defined as the ratio:

$$\mathrm{I_R} = \frac{\mathrm{CI}}{\mathrm{RI}}$$

where RI is the corresponding average random value of CI for an $n \times n$ matrix. The values of RI are shown (Saaty, 1980) in Table II.

The judgements can be considered acceptable if $\mathrm{I_R} \leq 0.1$. In cases of inconsistency, the assessment process for the inconsistent matrix is immediately repeated. An inconsistency ratio of 0.1 or more may warrant further investigation.

(4) For each decision criterion, calculate the overall preference rating on a scale of from 0.000 to 1.000 with which each decision alternative is likely to achieve its objective. The synthesis of judgements is obtained as a result of hierarchic "re-composition" in order to reach the best decision.

After its introduction by Saaty, AHP has been widely used in many applications (Vargas, 1990). Designed to reflect the way people actually think, the AHP was developed more than 20 years ago and continues to be the most highly regarded and widely used decision-making theory.

AHP and MAFMA theory: a case study

The actual case study here proposed deals with an important Italian refrigerator manufacturer. The refrigerator manufacturing process is described in Figure 1.

By virtue of the high level of saturation and the number of corrective maintenance interventions required in the past, the most three critical departments are the following:

(1) plastic part production;
(2) metal part production;
(3) insulation foam injection of the refrigerator doors.

To improve the plant reliability performance, a MAFMA analysis of the machines belonging to these departments is executed.

Table II.
RI values for different matrix orders (Saaty, 1980).

n	1	2	3	4	5	6	7
RI	0	0	0.52	0.89	1.11	1.25	1.35

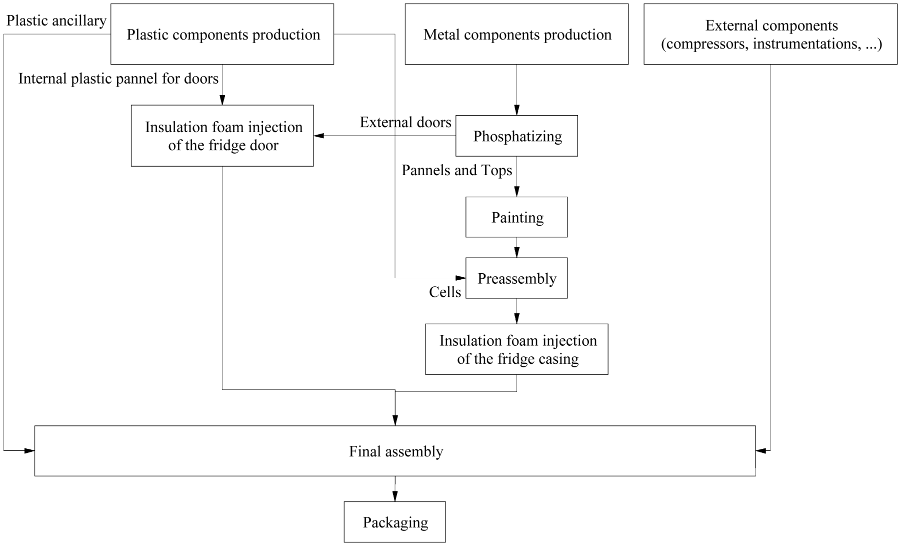

Figure 1.
Refrigerator production process scheme

The effect of each possible cause of failure is evaluated in function of four performance criteria:

(1) chance of failure;

(2) chance of non-detection;

(3) failure severity; and

(4) expected cost.

The evaluation of each attribute is obtained in different ways, if possible, defining a rational method to quantify the single criterion for each cause of fault, 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 10) to take into account the different criticality levels. The scores have then been defined in accordance with the experiences of the maintenance personnel. Alternatively, if a "quantitative" analysis of the attribute is evaluated too difficult and/or vague by maintenance staff, a "qualitative" pairwise comparison between the different causes of fault with respect to the criterion analysed is adopted. A brief description of the method and technical data used to assign the different scores is shown in the following.

Chance of failure

The chance of failure is evaluated as a function of the MTBF (Table III). The few available MTBF values collected in the past by the company are then integrated by the experiences of the maintenance personnel. Just as an indication, Table III reports an estimation of percentage of failure corresponding to one day of work.

Chance of non-detection

The chance of non-detection is evaluated adopting the score reported in Table IV. The scores are defined in accordance with the experiences of the maintenance staff. It is evident that the more a failure is visible the more its probability of detecting grows. "Controllable via switchboard" means, for example, the presence of auto-analysis programs and/or automatic sensors to find some anomaly in the process.

Failure severity

In terms of safety, the severity of the failure effect is calculated adopting the score reported in Table V. As one can see, the linguistics judgements are completely devoted to work (i.e. manpower) safety aspects. In particular, three days of absence due to an accident at work represent in Italy an important limit. When the absence is longer than three days, the company must communicate the accident to the Italian institution for the accidents at work (INAIL: Istituto Nazionale Infortuni sul Lavoro) to obtain the insurance cover. On the other side, INAIL also opens an investigation into the company to find out possible responsibilities.

Table III.
Scales used to measure estimates of the chance of failure

Linguistic evaluation of the probability of failure occurrence	Corresponding MTBF	Score	Occurrence rates (%)
Remote	> 10 years	1	< 0.01
Low	2-10 years	2-3	0.01-0.1
Moderate	6 months-2 years	4-6	0.1-0.5
High	3-6 months	7-8	0.5-1
Very high	< 3 months	9-10	> 1

Table IV.
Scales used to measure estimates of the chance of non-detection

Visible to the naked eye			Controllable via switchboard			Visible after an inspection		Periodical inspection		
Yes	Partially	No	Directly	Indirectly	No	Yes	No	Yes	No	Score
×										1
		×	×							1
	×					×				2
		×		×		×		×		3
		×		×		×			×	4
	×						×	×		5
		×		×			×	×		5
	×						×		×	6
		×		×			×		×	6
		×			×	×		×		7
		×			×	×			×	8
		×			×		×	×		9
		×			×		×		×	10

Expected cost

The economical aspects of a failure are calculated using a "qualitative" pairwise comparison. This choice is due to the incapability of doing a precise evaluation by the maintenance staff. Two aspects should be considered to obtain a reliable "score-table" based on linguistic evaluations of failure costs: production loss, maintenance manpower, spare parts, "domino effects", non conforming products produced, etc. Then, the numerous aspects that influence the cost of a failure, added to the few available data and the imprecise evaluations obtained by the maintenance personnel, suggest the adoption a pairwise comparison approach.

The MAFMA application here reported is relevant to the insulation foam injection line for the production of the refrigerator doors. Table VI presents the failure mode analysis of a primary element of this line: the hydraulic system. This presentation is equivalent to a FMECA. The table also reports the "direct" numerical evaluations for the three conventional FMECA parameters (chance of the failure S_f, severity of its failure effect S, and the chance of the failure being undetected S_d) estimated as described above. The corresponding RPNs are also shown in the last column.

Table VII reports the pairwise judgements relevant to the different causes of failure in terms of the qualitative expected cost factor.

In designing the AHP hierarchical tree, the aim is to develop a general framework that satisfies the needs of the analysts to solve the selection problem of the most critical failure cause. The AHP starts by decomposing a complex, multi-criteria problem into a hierarchy where each level consists of a few manageable elements which are then decomposed into another set of elements (Wind and Saaty, 1980).

The AHP hierarchy developed in this study is a three-level tree in which the top level represents the main objective of fault cause selection and the lowest level consists of the alternative (possible) causes of failure. The evaluation criteria that influence the primary goal are included at the second level and are related to all aspects considered in this paper: chance of failure, chance of not detecting a failure, severity and expected cost. The overall AHP structure is shown in Figure 2.

Severity	Score
We will probably not notice	1
Slight annoyance	2
	3
Accident requiring less than three days of absence	4
	5
	6
Accident requiring more than three days of absence	7
	8
Accident with safety-regulatory consequences	9
	10

Table V.
Scales used to measure estimates of the failure severity

Table VI.
A conventional scheme to present failure analysis results

System: insulation foam injection line
Primary element: hydraulic system

Component	Function	Potential failure mode	Potential effect of failure	Potential cause of failure	S_f	S_d	S	*RPN*
Solenoid valves	To control the piston's stroke	Breaking	Piston does not execute the movement	Magnet burned (Cause A)	3	2	2	12
Hydraulic pistons	To carry out the movements	Blow-by	Loss of oil	Breaking of seal (Cause B)	5	5	3	75
		Breaking	Piston does not execute the movement	Breaking of piston rod (Cause C)	2	2	5	20
Pressure regulator	To control the pressure	Breaking	Pressure out-of-range	Mechanical stress (Cause D)	6	2	9	108
High pressure tubes	To contain the fluid	Breaking	Loss of fluid	Overpressure (Cause E)	2	2	10	40
Hydraulic gearcase	To maintain the oil in pressure	Breaking	Lack of pressure for the movements	Pump wear (Cause F)	1	8	2	16
				Breaking of electrical engine (Cause G)	2	6	6	72
		Pressure out-of-range	Irregular functioning	Breaking of pressure switch (Cause H)	3	6	9	162
		Loss of oil	Lowering of oil level	Blow-by (Cause I)	6	5	3	90

	Cause A	Cause B	Cause C	Cause D	Cause E	Cause F	Cause G	Cause H	Cause I
Cause A	–	1/4	1/5	1/5	1/5	1/6	1/5	1/2	1/2
Cause B	4	–	1/2	1/2	1/2	1/3	1/2	3	3
Cause C	5	2	–	2	2	1/2	1	4	4
Cause D	5	2	1/2	–	1	1/2	1	4	3
Cause E	5	2	1/2	1	–	1/2	1	4	3
Cause F	6	3	2	2	2	–	2	5	4
Cause G	5	2	1	1	1	1/2	–	4	4
Cause H	2	1/3	1/4	1/4	1/4	1/5	1/4	–	1/2
Cause I	2	1/3	1/4	1/3	1/3	1/4	1/4	2	–

Note: Inconsistency ratio = 0.02

Table VII.
Failure expected cost evaluation

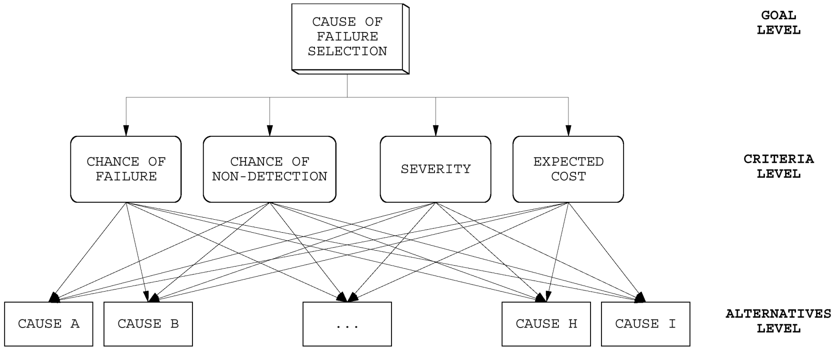

Figure 2.
The AHP hierarchical representation of causes of failure analysis

After defining the hierarchy, the AHP requires the use of a measurement methodology to establish priorities among the elements within each level of the hierarchy. As reported above, both qualitative and quantitative criteria can be compared using informal judgements to derive the priorities.

A pairwise comparison at the first level of the hierarchy is executed in order to obtain value judgements. Table VIII reports the pairwise comparisons given by the maintenance staff in terms of the four criteria proposed for the failure cause analysis problem.

The prioritisation of the performance criteria is achieved by the composition of pairwise comparisons. The final prioritisation is reached by calculating the normalised components of the right eigenvector of the final matrix

	Probability of failure	Probability of non-detection	Severity	Expected cost	Priority
Probability of failure	–	3	1	1	0.302
Probability of non-detection	1/3	–	1/2	1/3	0.111
Severity	1	2	–	1/2	0.230
Expected cost	1	3	2	–	0.358

Note: Inconsistency ratio = 0.02

Table VIII.
Criteria priorities evaluation

corresponding to the maximum eigenvalue of the same matrix. A short computational way to obtain this ranking is to rise the pairwise matrix to powers that are successively squared each time. The row sums are then calculated and normalised. Finally, this process is iterated and stopped when the difference between these sums in two consecutive calculations is smaller than a prescribed value.

As one can see in Table VIII, the priorities for criteria (i.e. the degree of importance) with respect to goal are computed as 0.302 for chance of failure, 0.111 for chance of not detecting a failure, 0.230 for severity, and 0.358 for expected cost. Note the acceptable value of the inconsistency ratio which is equal to $0.02 < 0.1$.

The prioritisation step is reiterated for the second hierarchical level. The priority that each cause of failure has with respect to the other causes of failure in terms of every criterion must be evaluated. For the "qualitative" expected cost criterion, the calculus is similar to the one presented above

The three "quantifiable" criteria can be evaluated normalising the quantitative factor evaluations. For example, using data reported in Table VI, for the factor "chance of failure" one obtains the results shown in Table IX.

After evaluating the different causes of failure with respect to the criteria considered, all judgements must be aggregated over the hierarchical tree. Table X reports the priorities for cause of failure with respect to the four criteria in local and global (i.e. priority of criterion × local priority of cause) terms respectively.

As soon as the prioritisation of performance criteria is achieved by the composition of pairwise comparisons, the final step implies the use of AHP framework to evaluate the different causes of failure. Table XI reports the final ranking for the nine causes of failure considered.

As shown in Table XI, cause "D" turns out to be the most critical failure problem among the nine alternatives, with an overall priority score of 0.155.

As one can see, the final MAFMA result differs from the FMECA one (see RPN column in Table VI). The most critical cause of failure is "D", which is characterised by a great severity even if with low level of chance of detection. This is due to the low importance assigned by the analyst in this case study to

Cause of failure	Score			Priority
Cause A	3	3/30	=	0.100
Cause B	5	5/30	=	0.167
Cause C	2	2/30	=	0.067
Cause D	6	6/30	=	0.200
Cause E	2	2/30	=	0.067
Cause F	1	1/30	=	0.033
Cause G	2	2/30	=	0.067
Cause H	3	3/30	=	0.100
Cause I	6	6/30	=	0.200
Total	30			1.000

Table IX.
Results obtained using data reported in Table VI

Criterion	Alternative	Local priority	Total priority	Criterion	Alternative	Local priority	Total priority
Chance of failure			0.302	*Severity*			0.230
	Cause A	0.100	0.030		Cause A	0.041	0.009
	Cause B	0.167	0.050		Cause B	0.061	0.014
	Cause C	0.067	0.020		Cause C	0.102	0.023
	Cause D	0.200	0.060		Cause D	0.184	0.042
	Cause E	0.067	0.020		Cause E	0.204	0.047
	Cause F	0.033	0.010		Cause F	0.041	0.009
	Cause G	0.067	0.020		Cause G	0.122	0.028
	Cause H	0.100	0.030		Cause H	0.184	0.042
	Cause I	0.200	0.060		Cause I	0.061	0.014
Chance of not detecting			0.110	*Expected cost*			0.358
	Cause A	0.053	0.006		Cause A	0.026	0.009
	Cause B	0.132	0.014		Cause B	0.087	0.031
	Cause C	0.053	0.006		Cause C	0.171	0.061
	Cause D	0.053	0.006		Cause D	0.129	0.046
	Cause E	0.053	0.006		Cause E	0.129	0.046
	Cause F	0.211	0.023		Cause F	0.234	0.084
	Cause G	0.158	0.017		Cause G	0.143	0.051
	Cause H	0.158	0.017		Cause H	0.036	0.013
	Cause I	0.132	0.014		Cause I	0.046	0.016

Table X.
Priorities of evaluation criteria and subcriteria with respect to the primary goal

Cause of failure	Evaluation
Cause D	0.155
Cause F	0.126
Cause E	0.119
Cause G	0.117
Cause C	0.111
Cause B	0.110
Cause I	0.105
Cause H	0.103
Cause A	0,055

Note: Overall inconsistency index = 0.01

Table XI.
The final ranking (sorted synthesis of leaf nodes with respect to goal)

the criterion "chance of detection" in Table IV. The most critical cause of failure "H" in FMECA is not so considered in MAFMA. This is due to the low cost impact of this type of failure (characterised by internal corrective maintenance with low MTTR values) and a low level of chance of failure, the two most important criteria in our MAFMA. A contrary speech can be done for cause "F".

Sensitivity analysis

Although this solution reflected a possible scenario where the expected cost and the chance of failure are the most important criteria, the model solution can change in accordance with shifts in analyst logic. To explore the response of model solutions (i.e. the solution robustness) to potential shifts in the priority of designer strategy, a series of sensitivity analyses of criteria weights can be performed by changing the priority (relative importance) of weights. As a matter of fact, every criterion is characterised by an important degree of sensitivity, i.e. the ranking of all causes of failure changes dramatically over the entire weight range (Min and Melachrinoudis, 1999). The problem is to control whether a few changes in the judgement evaluations can lead to significant modifications in the priority final ranking or not.

For this reason, sensitivity analysis is used to investigate the sensitivity of the alternatives to changes in the priorities of the criteria immediately below the goal. The analysis here proposed emphasises the priorities of the four criteria in the MAFMA model and how changing the priority of one criterion affects the priorities of the others. Evidently, as the priority of one of the criteria increases, the priorities of the remaining criteria must decrease proportionately to their original priorities, and the global priorities of the alternatives must be recalculated. All the results reported in Table XII are obtained using the Expertchoice software, a multi-attribute decision tool which has supported all the MAFMA application reported in this paper.

Criteria	Decreasing ...	Relative priority value in final solution	Increasing ...
Chance of failure	Cause "D" is reached and overcome by cause "F" (priority equal to 16.1 per cent) and cause "E" (5.3 per cent)	30.2 %	Cause "D" always the best; a growth of the importance of cause "I" can be also noted
Chance of non-detection	Cause "D" always the best; the importance of cause "F" decreases as far as 4° position for 0 per cent of criterion weight	11.0%	Cause "D" is reached and overcome by cause "F" (priority equal to 24.8 per cent) and cause "G" (34.1 per cent). If we continue to increase the weight "F" is always in first position while "D" loses position
Severity	Cause "D" is reached by "F" but only reducing the severity priority as far as 4.1 per cent	23.0%	Cause "D" is reached by cause "E" (priority equal to 72.1 per cent) and cause "H" (100 per cent). The importance of cause "F" evidently decreases
Expected cost	Cause "D" always the best; the importance of cause "F" collapses	35.8%	The priority of cause "D" tends to decrease. It is reached and overcome by cause "F" (priority equal to 49.6 per cent) and cause "C" (68.4 per cent)

Table XII.
Observations derived from sensitivity analysis of the criteria priority values

For example, decreasing the (relative) importance of the expected cost, the cause "D" appears to remain always the most critical type of fault. Increasing the attribute importance from 35.8 per cent to 49.6 per cent, "F" reaches and overcomes "D" as most critical cause of failure. For a weight/priority equal to 68.4 per cent "D" is also reached by cause "C".

As one can see from Table XII, the most critical cause of failure "D" is robust enough. In fact, it is generally necessary to give great changes in the criteria to obtain causes more critical than "D". In any case, the importance of "D" never collapses. This is not so true for cause "F", which results are more sensible to factor priority alterations. Then, the MAFMA selection of "D" as the most critical cause of failure can be accepted with a good degree of confidence from company maintenance staff.

We conclude this section with two final considerations. First, the sensitivity analysis here proposed is only relevant to the priorities of the four criteria. Second, on account of the fact that we have changed each attribute weight one at a time, only the "main effects" have been considered. In other words, "interaction effects" of the changes in two or more weights have been neglected. These simplifications have been adopted for the following reasons:

- The final solution is evidently mainly sensible to changes in the priorities of the highest level of the hierarchy;
- The introduction of the interaction effects makes the sensitivity analysis too complex for actual applications. Nevertheless, it is necessary to note that the main effects are generally the most important aspects in a sensitivity analysis.

In other words, the easy and intuitive approach here following seem to be a good compromise between costs and benefits, efficiency and efficacy.

Conclusions

Multi-attribute failure model analysis (MAFMA) appears to be a powerful tool for performing a complete criticality analysis on prioritising failures identified in a reliability study for corrective actions. MAFMA makes it possible to obtain a ranking of failure causes which includes several type of information (failure rate, non-detection, severity, expected cost for each fault). In particular, the use of an AHP-based approach for the multi-attribute analysis provides a framework with interesting characteristics for the selection process of the most critical cause of failure. The AHP method helps a designer to work in a systematic and analytical manner, addressing in turn each aspect of the failure in the hierarchy. Qualitative and subjective judgements involving a number of people can be included in the priority setting process. In fact, by using a series of pairwise judgements, AHP is able to manage the dilemma derived from a "direct" (quantitative) evaluation of intangible (qualitative) criteria, overcoming the problem to assign a score based on tables reporting vague and unreliable linguistic evaluations. However, one can note that, if reliable quantitative judgements are available for some criteria, they can easily be included in AHP analysis. This possibility means that MAFMA can also eventually easily replace or integrate in a more complete manner FMECA studies already executed by maintenance staff.

Another advantage can not be neglected in terms of a practical use of AHP technique. Similar to FMECA, all AHP steps are well supported by commercial software. Thanks to this software, the decision maker is able to execute complex failure analyses in a quick and intuitive manner. In particular, a sensitivity analysis can be easily conducted to test the robustness of the final cause failure ranking obtained, underlining eventual criticisms of some subjective evaluations given by the maintenance personnel. This important property is not normally proposed, as known to the author, in actual FMECA applications.

In conclusion, the use of the AHP can provide an effective way of quantifying and ranking critical failures at the design stage. The proposed approach forms a basis for a continuous process of product/process reliability design as the hierarchies and the priorities of the elements can be easily modified and updated. Future applications could include other important aspects such as assurance problems, access difficulty, environmental impact, etc. The definition of a general and standard MAFMA hierarchy could represent an interesting argument worthy of successive investigations. New actual implementations of this new methodology are also suggested.

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