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SCENARIO-BASED FMEA: A LIFE CYCLE COST PERSPECTIVE

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ABSTRACT

Failure Modes and Effects Analysis (FMEA) is a method to identify and prioritize potential failures of a product or process. The traditional FMEA uses three factors, Occurrence, Severity, and Detection, to determine the Risk Priority Number (RPN). This paper addresses two major problems with the conventional FMEA approach: 1) The Detection index does not accurately measure contribution to risk, and 2) The RPN is an inconsistent risk-prioritization technique.

The authors recommend two deployment strategies to address these shortcomings: 1) Organize the FMEA around failure scenarios rather than failure modes, and 2) Evaluate risk using probability and cost. The proposed approach uses consistent and meaningful risk evaluation criteria to facilitate life cost-based decisions.

KEYWORDS: FMEA, FMECA, Risk Priority Number (RPN), reliability, risk management

1. INTRODUCTION

While FMEA is considered a tool to help improve reliability, it can also guide improvements to the serviceability and diagnosability of a system (Di Marco et al., 1995: Lee, 1999). However, product development teams must balance risk reduction strategies (improved reliability, serviceability and diagnostics) with cost.

Companies are aware of warranty costs associated with product failures. Additionally, many companies now offer long-term service contracts, making the manufacturer responsible for costs formerly borne by the customer. Now more than ever, companies need to make cost-driven decisions when compromising between the risk of failure and the cost of abatement. The Risk Priority Number (RPN), used to evaluate risk in FMEA, is not sufficient for making cost-driven decisions. At best, the RPN provides a qualitative assessment of risk. In addition, components of the RPN (Severity, Detection, and Occurrence) have inconsistent definitions, resulting in questionable risk priorities.

This paper introduces a scenario-based FMEA to delineate and evaluate risk events more accurately.

> *Scenario-based FMEA is an FMEA organized around undesired cause–effect chains of events rather than failure modes. Scenario-based FMEA uses probability and cost to evaluate the risk of failure.*

The purpose of scenario-based FMEA is to improve the representation of failures, and to evaluate these failures with consistent and meaningful metrics. This approach facilitates economic decision-making about the system design. Table 1 shows a rough comparison between traditional FMEA, serviceability design, and scenario-based FMEA.

Table 1 Comparison of risk-reduction techniques

method	*strategy*	*failure probability*	*cost of failure*	*product cost*	*total life cost*
traditional FMEA	↑ reliability	↓	same	↑	?
serviceability design	↓ service cost	same	↓	↑	?
scenario-based FMEA	↓ life-cycle cost (failure cost and product cost)	cost-based decision	cost-based decision	cost-based decision	↓

Traditional FMEA is usually focused on improving product reliability – often at the expense of product cost. Serviceability design reduces the cost of the failure (if failure does occur) but generally adds to product cost through design changes. Scenario-based FMEA can be used to weigh the expected cost of the failure against the estimated cost of the solution strategy.

The next section covers definitions of the Risk Priority Number. Section 3 discusses shortcomings of traditional FMEA and the RPN. Section 4 compares scenario-based FMEA to traditional FMEA using a hair dryer and video projector as illustrative examples. Section 5 concludes with advantages of scenario-based FMEA and lists promising opportunities for future research.

2. INTRODUCTION TO FMEA

FMEA is a method to help identify and rank potential failures of a design or a process. Table 2 outlines the three major phases of the FMEA.

Table 2 Three major categories of FMEA Tasks

FMEA Task	***Result***
Identify Failures	Describe failures: Causes → Failure Modes → Effects
Prioritize Failures	Assess Risk Priority Numbers (**RPN**): **RPN** = failure occurrence × effects severity × detection difficulty
Reduce Risk	Reduce risk through: reliability, test plans, manufacturing changes, inspection, etc.

The FMEA team identifies, evaluates, and prioritizes potential failures. The method helps focus resources on high "risk" failure modes. Next, the team attempts to lessen risk by reducing failure frequency and severity.

The FMEA emerged in the 1960's as a formal methodology in the aerospace and defense industries. Since then, it has been adopted and standardized by many industries worldwide. Table 3 lists several FMEA procedures published since 1964.

Table 3 A partial list of FMEA Publications

year	**FMEA Document**
1964	"Failure Effect Analysis" Transactions of the NY Acad. of Sciences (J.S. Couthino)
1974	US Department of Defense (DoD) Mil-Std-1629 (ships) "Procedures for Performing a Failure Mode, Effects, and Criticality Analysis"
1980	US DoD Mil-Std-1629A
1984	US DoD Mil-Std-1629A/Notice 2
1985	International Electrochemical Commission (IEC) 812 "Analysis techniques for system reliability – procedure for failure mode and effects analysis"
1988	Ford published "Potential Failure Modes and Effects Analysis in Design and for Manufacturing and Assembly Processes Instruction Manual"
1994	SAE J1739 Surface Vehicle Recommended Practice
1995	"FMEA: from theory to execution" (D.H. Stamatis):
1995	"FMEA: predicting and preventing problems before they occur" (P. Palady)
1996	Verbrand der Automobil industrie, Germany VDA Heft 4 Teil 2:
1996	"The Basics of FMEA" (R.E. McDermott et. al.)
1998	Proposal for a new FMECA standard for SAE (J. Bowles)

2.1 What is a Failure Mode?

The Automotive Industry Action Group (1995) definition of a failure mode is similar to definitions used in many FMEA standards (SAE 1994, Stamatis 1995).

> *Failure Mode – the manner in which a component, subsystem, or system could potentially fail to meet the design intent. The potential failure mode could also be the cause of a potential failure mode in a higher level subsystem, or system, or the effect of a lower level effect.*

This definition helps distinguish between causes, failure modes, and effects, depending on the level of the analysis. A failure mode can simultaneously be considered a cause and an effect and is therefore a "link" in the cause-effect chain.

2.2 The Risk Priority Number (RPN)

The RPN is used by many FMEA procedures to assess risk using these three criteria:

- **Occurrence (O)** – how likely is the cause to occur and result in the failure mode?
- **Severity (S)** – how serious are the end effects?
- **Detection (D)** – how likely is the failure to be detected before it reaches the customer?

The RPN is the product of these three elements.

$$RPN = O \times S \times D \qquad (1)$$

The definitions of the RPN elements will be described in the following sections.

2.2.1 Probability of Occurrence (O)

Occurrence is related to the probability of the failure mode and cause. Occurrence is *not* related to the probability of the end effects. The Occurrence values are arbitrarily related to probabilities or failure rates (Table 4).

Table 4 Occurrence criteria (adapted from AIAG, 1995)

Probability of Failure	**Failure Rates**	**Occurrence**
Very High:	≥ 1 in 2	10
Failure is almost inevitable	1 in 3	9
High:	1 in 8	8
Repeated Failures	1 in 20	7
Moderate:	1 in 80	6
Occasional failures	1 in 400	5
	1 in 2,000	4
Low:	1 in 15,000	3
Relatively few failures	1 in 150,000	2
Remote: Failure unlikely	1 in 1,500,000	1

2.2.2 Severity of Effect (S)

Severity measures the seriousness of the effects of a failure mode. Severity categories are estimated using a 1 to 10 scale, for example:

10 Total lack of function and a safety risk
⋮
8 Total lack of function
⋮
4 Moderate degradation of performance
⋮
1 Effect almost not noticeable

Severity scores are assigned only to the effects and not to the failure mode or cause.

2.2.3 Detection (D)

The definition of Detection usually depends on the scope of the analysis. Definitions usually fall into one of three categories

i) Detection during the design & development process
ii) Detection during the manufacturing process
iii) Detection during operation

Two interpretations are described in this section.

> *Detection Definition 1: The assessment of the ability of the "design controls" to identify a potential cause or design weakness before the component or system is released for production.*

Detection scores are generated on the basis of likelihood of detection by the relevant company design review, testing programs, or quality control measures. This definition evaluates the internal quality and reliability systems of an organization (Palady, 1995).

> *Detection Definition 2: What is the chance of the customer catching the problem before the problem results in catastrophic failure?*

The rating decreases as the chance of detecting the problem is increased, for example:

10 – Almost impossible to detect
⋮
1 – Almost certain to detect

This definition measures how likely the customer is to detect the failure based on the systems diagnostics and warnings, or inherent indications of pending "catastrophic" failure.

3. SHORTCOMINGS OF TRADITIONAL FMEA

3.1 What is Risk?

The purpose of FMEA is to prioritize potential failures in accordance with their "risk." There are many definitions of risk, and we have listed a few below

- The possibility of incurring damage (Hauptmanns and Werner, 1991)
- Exposure to chance of injury or loss (Morgan and Henrion, 1990)
- Possibility of loss or injury,… uncertain danger (Webster's Dictionary, 1988)

Most definitions of risk contain two basic elements: 1) chance: possibility, uncertainty, probability, etc., and 2) consequences: cost, hazard, injury, etc. Kaplan and Garrick (1981) maintain that risk quantification should evaluate the following questions:

- How likely is the scenario to happen?
- (If it does happen) what are the consequences?

The first question addresses the possibility of an undesired event. The second question attempts to quantify the loss or hazard associated with the failure. We will use these principles to examine the elements of the Risk Priority Number.

3.2 "Occurrence" Evaluates the Probability of the Failure Mode and its Cause

The Occurrence rating reflects the probability of the cause and the immediate failure mode and not the probability of the end effect (AIAG, 1995: Stamatis, 1995). Consider two possible situations associated with a grease fire in a kitchen:

i) a grease fire resulting in damage to the kitchen only, and
ii) a grease fire where the building burns down.

The Occurrence rating for these two scenarios would be identical although, intuitively, we know that damage to the kitchen is more likely than the building burning down.

According to the definitions of risk, we are ultimately interested in the probability of the cause *and* resulting effect. The two scenarios related to the fire have different probabilities (and outcomes) and therefore pose different risks. The different probabilities would not be reflected using the Occurrence index.

3.3 Confusion Associated with the "Detection" Index

One definition of Detection relates to the quality processes of an organization. This definition quantifies how likely the company's "controls" are to detect the failure mode during the product development process. There is some confusion associated with this definition, for example: If a "design control" detects a failure mode, does this imply it will be prevented? How can we *quantify* the competency of quality processes? If a potential failure is identified as a line item on an FMEA, has it already been "detected"?

Controls used by the organization can help identify potential failures (e.g. design reviews, reliability estimation, modeling, testing) and estimate the probability of a failure. However, this is an *organizational* issue, rather than a *product* issue. Assessing the effectiveness of an entire development effort is extremely difficult and highly subjective.

Another definition of Detection relates to the detectability of a failure once the product is in the hands of the customer. Once the product is in operation, "Detection" reflects the probability that the failure will occur in one mode (detected early) versus another (undetected until 'catastrophic' failure). For example, FMEA might list an oil leak resulting in engine failure with a low Detection rating (easy to detect) due to a prominent oil warning light. However, the RPN will give a low priority to a very frequent oil leak that is easy to detect, even if this is the mostly costly failure over the life of the engine.

Having multiple definitions for Detection begs the question: *which definition, if any, measures contribution to risk?* Risk is composed of chance and consequences: the chance component should reflect the probability of the cause *and* the specified consequences. If "probability of Occurrence" rates the probability of the cause, then Detection should represent the conditional probability of realizing the ultimate consequences (given the cause.)

We propose that the Detection rating should either be re-defined as a conditional probability or omitted from the FMEA procedure altogether. Some alternative rankings of risk recommend using only combinations of Occurrence vs. Severity to prioritize risk (SAE, 1994: Palady, 1995); Detection is conspicuously absent from these prioritization schemes.

3.4 Inconsistent Values are Assigned to the RPN Elements

The numbers used for Occurrence, Severity, and Detection do not carry any special meaning and so their basic definitions vary. Figure 1 shows four recommended relationships between Occurrence and probability.

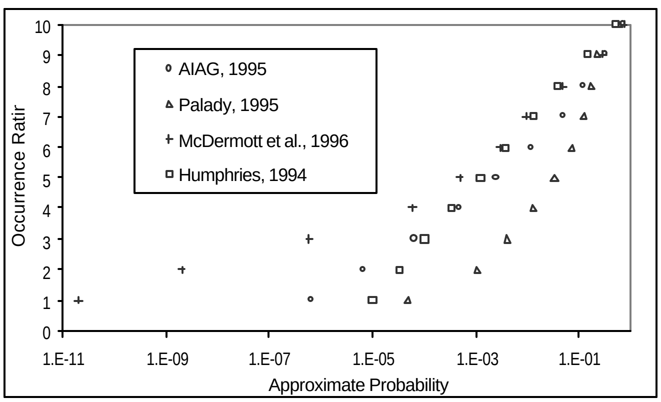

Figure 1 Occurrence rankings and probabilities

An Occurrence rating of "5" could correspond to failure rates which span several orders of magnitude (e.g. from around 0.1 to 0.001 in Figure 1).

The ratings for Severity are not related to any standard measure. These 1-10 values can only provide a relative ranking of "consequences" or "hazard" for a particular FMEA.

Detection is not related directly to probability or any other standard measure (with the exception of some "process FMEA" manuals). In addition, Detection has several disparate definitions as we've discussed.

3.5 Measure Theoretic Perspective on the RPN

The scales for Severity, Occurrence, and Detection are ordinal. Ordinal scales are used to rank-order items such as the size of eggs, or quality of hotels. Ordinal measures preserve transitivity (order) but their magnitude is not "meaningful." For example, an Occurrence rating of 8 is more likely than 4 but it is not twice as likely. The 1-10 numbers are categories for which using letters categories would also be appropriate. It is valid to rank failures along a single ordinal dimension (e.g., "Severity") *but multiplying ordinal scales is not an "admissible" transformation* (Mock and Grove, 1979).

The magnitude of the RPN is used to prioritize failure risks. However, the magnitude of the RPN is not meaningful since it is the product of three ordinal indices. Perhaps using letter-categories would be favorable since we would not be tempted to multiply categories. The definitions and calculations associated with the RPN raise the question: *Is the RPN a valid measure of risk?* Section 4 demonstrates the inconsistencies of the RPN with respect to another risk metric: expected cost.

4. SCENARIO-BASED FMEA USING EXPECTED COST

The focus of FMEA should center on identifying undesired causes and effects. If a "cause" has a cause, then the cause-effect chain should be lengthened to accommodate the additional information. Traditional FMEA spreadsheets limit failure representation by only providing a few columns to describe an entire fault chain (Lee, 1999). In addition, the analysis is organized around failure modes, which are an arbitrary "link" in the cause-effect chain. Ultimately, we are not so concerned with whether "cracked pipe" is a cause, failure mode, or an effect, but rather:

- What could cause the failure?
- What are the potential effects on the system?
- How likely is the cause to occur and result in the specified effects?

There is a risk associated with the *scenario*, that is, the series of causes and effects.

> *A failure scenario is an undesired cause-and-effect chain of events. Each scenario can happen with some probability and results in negative consequences.*

The cause-effect chain can be lengthened when new effects and causes of "causes" are identified. Failure scenarios are used frequently in the Risk Analysis field (Kaplan and Garrick, 1981: Modarres, 1992). The difference between failure modes and scenarios is as follows

- *failure mode* describes a cause and the immediate effect
- *failure scenario* is an undesired cause-effect chains of events, from the initiating cause to end effect, including all intermediate effects (Figure 2.)

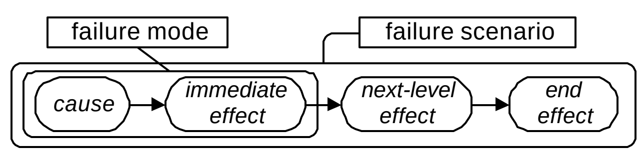

Figure 2 Failure modes and scenarios

Each failure scenario happens with some probability and results in negative consequences. For example, brake failure in an automobile could cause an accident while carrying one passenger or four: these are different scenarios with distinct probabilities and consequences. It may not be necessary to differentiate between "accident with one passenger" and "accident with four passengers," but scenario-based FMEA can accommodate this granularity. Different causes can be listed for each scenario, such as "low fluid pressure" or "linkage failure" and causes for these events can be added. Figure 3 shows a map of potential failure scenarios for a brake system failure.

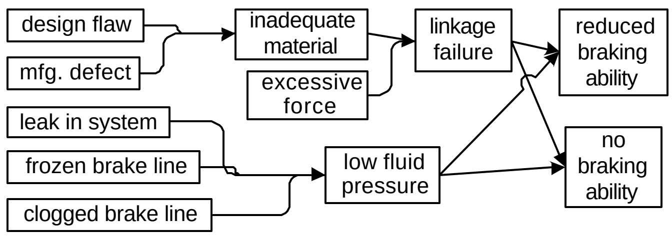

Figure 3 Scenario map for brake failures

There are 12 independent paths, or failure scenarios, and each is listed as a line item on the FMEA. Risk ratings measure the probability and consequences of each scenario. For instance, an oil leak could result in equipment failure. Traditional FMEA would list this as a single line item with an Occurrence (assigned to the cause), Severity (assigned to the equipment damage) and Detection rating (assigned to how likely the oil leak would be discovered before the end effect is realized). Scenario-based FMEA would list the failures as three line items, each with an assessed probability and consequence:

i) Oil leak, warning light goes on, signal is detected and operation is ceased (consequence1, probability1)

ii) Oil leak, warning light goes on, signal goes undetected, operation continues and equipment is damaged (consequence2, probability2)

iii) Oil leak, no warning light, operation continues and equipment is damaged (consequence2, probability3)

Risk should be evaluated separately since each scenario has an associated probability and consequence. Similarly, defects in a manufacturing line result in different failure scenarios: they can be "detected" at discrete points during production or after they have been shipped, with differing probabilities and consequences.

According to Bayes' theorem, scenario probability is the probability of the cause *and* conditional probability of the end effect (Lindley, 1965). Scenario-based FMEA accommodates a) multiple causes that could result in a single end effect, b) single causes that result in multiple effect. Figure 3 shows examples of failure scenarios throughout a products life cycle.

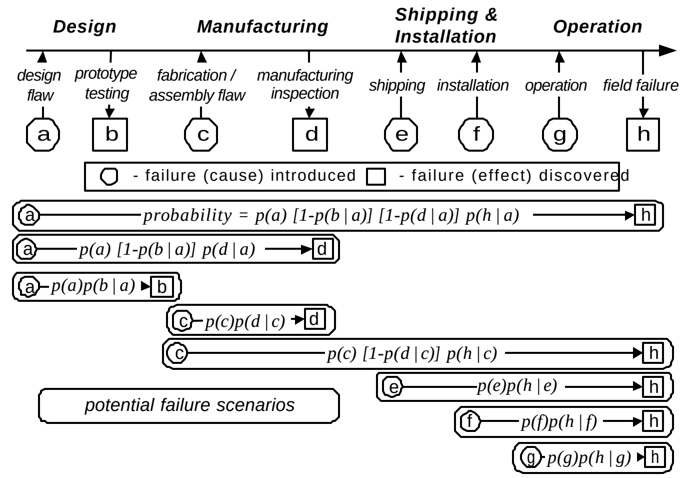

Figure 4 Failure scenarios in a product's life cycle

Failures can be introduced at many points and discovered at various instances downstream. For example, a design flaw (point *a* in Figure 4) might be discovered during prototype testing (point *b*), during manufacturing inspection (point *d*), or during operation (point *h*). Each scenario has a "risk" associated with its probability and consequences.

4.1 "Expected Cost" as a Measure of Risk

In section 3 we explained how risk contains two basic elements: chance and consequences. Probability is a universal measure of chance, and cost is an accepted measure of consequences (Gilchrist, 1993). For a given failure scenario, risk calculated as *expected cost*: the product of probability and failure cost (Rasmussen, 1981: Modarres, 1992). Expected cost is used extensively in the fields of Risk Analysis, Economics, Insurance, Decision Theory, etc. Both probability and cost are ratio scales, for which multiplication is an admissible operation. For any scenario *i*

$$\textit{expected cost}_i = p_i \times c_i \tag{2}$$

Total risk for *n* scenarios can be expressed as follows

$$\textit{total expected failure cost} = \sum_{i=1}^{n} p_i c_i \tag{3}$$

Figure 4 shows the composition of the expected cost equation for scenario *a–d* (from Figure 4).

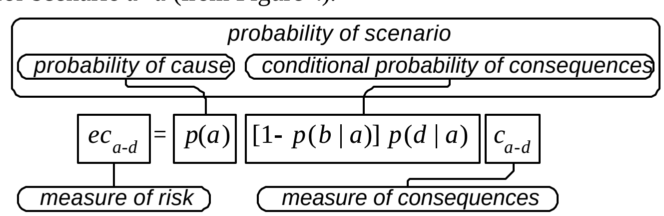

Figure 5 Composition of expected cost

Expected costs for the eight scenarios introduced in Figure 4 are expressed as:

$$ec_{a-b} = p(a)\,p(b|a)\,c_{a-b} \quad (4)$$

$$ec_{a-d} = p(a)\,[1- p(b|a)]\,p(d|a)\,c_{a-d} \quad (5)$$

$$ec_{a-h} = p(a)\,[1- p(b|a)]\,[1- p(d|a)]\,p(h|a)]\,c_{a-h} \quad (6)$$

$$ec_{c-d} = p(c)\,p(d|c)\,c_{c-d} \quad (7)$$

$$ec_{c-h} = p(c)\,[1- p(d|c)]\,p(h|c)\,c_{c-h} \quad (8)$$

$$ec_{e-h} = p(e)\,p(h|e)\,c_{e-h} \quad (9)$$

$$ec_{f-h} = p(f)\,p(h|f)\,c_{f-h}(10)$$

$$ec_{g-h} = p(g)\,p(h|g)\,c_{g-h} \quad (11)$$

Total risk for this example is the sum of the expected costs for all failure scenarios. In addition, failure costs associated with a specific cause can be calculated easily. For example, if a cause (i) has (n) potential effects, we could calculate the expected cost associated with this cause as

$$ec_i = p(i) \sum_{j=1}^{n} p(j|i)c_{i-j} \quad (12)$$

From equations 4-6, the total risk associated with cause "a" would be

$$\begin{aligned} ec_a &= ec_{a-b} + ec_{a-d} + ec_{a-h} \quad (13) \\ &= p_{a-b}\,c_{a-b} + p_{a-d}\,c_{a-d} + p_{a-h}\,c_{a-h} \\ &= p(a)\Big[p(b|a)c_{a-b} + [1\text{-}p(b|a)]\;p(d|a)c_{a-d} \\ &\qquad + [1\text{-}p(b|a)][1\text{-}\,p(d|a)]p(h|a)c_{a-h}\Big] \end{aligned}$$

Similarly, expected costs could be calculated for a given end event, using the probability of all contributing causes. This technique yields cost estimates that aren't possible using the Risk Priority Number. For comparison, Figure 6 shows the composition of the RPN.

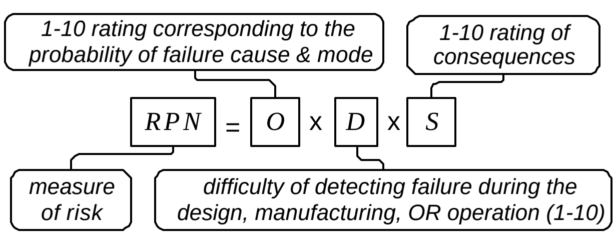

Figure 6 Composition of the Risk Priority Number

Expected cost has an infinite range of values, but the RPN is restricted to integer values between 1 and 1000. The RPN effectively expands a 0-1 probability into a 1-100 component (Occurrence $\times$ Detection) and compresses the measure of consequences into a 1-10 range (Severity.)

Gilchrist (1993) was among the first to recommend supplanting the RPN with expected cost. We build on Gilchrist's ideas in the next section by performing a detailed comparison between expected cost and the RPN.

4.2 Comparing the RPN to "Expected Cost"

This section shows a detailed comparison of the Risk Priority Number and expected cost. Our analysis is based on the following assumptions:

Assumption 1: ***A table relating Occurrence to probability***

We assume a table mapping probability to a 1-10 Occurrence scale, similar to the relationships shown in Figure 1.

Assumption 2: ***A table relating Severity to cost***

We assume there is a cost metric that is a continuous measure of consequences, and this cost is mapped to a 1-10 Severity rating. Figure 7 shows examples of hypothetical cost-Severity relationships for different industries.

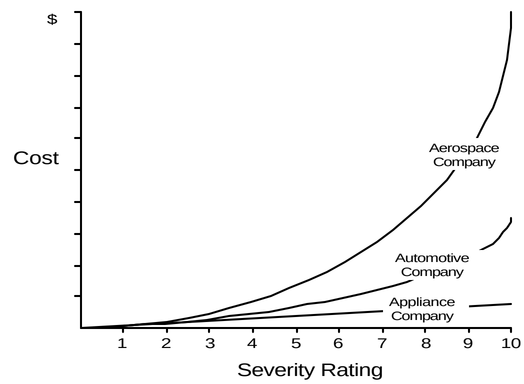

Figure 7 Hypothetical Cost-Severity relationships

Other "cost" metrics could be substituted, such as toxicity levels, fatalities, etc., as long the magnitude of the measure is meaningful. Specific examples of cost functions are shown in Table 5.

Table 5 Examples of cost-Severity tables

linear		exponential		hybrid	
Severity	Cost ($)	Severity	Cost ($)	Severity	Cost ($)
1	50	1	10	1	20
2	100	2	50	2	100
3	150	3	200	3	400
4	200	4	700	4	1000
5	250	5	2500	5	2000
6	300	6	10000	6	3500
7	350	7	35000	7	6000
8	400	8	130000	8	10000
9	450	9	500000	9	15000
10	500	10	2000000	10	20000

Assumption 3: ***Detection is omitted from RPN calculations***

For this example, we will set the Detection rating equal to 1 for all failures. We assume that the "probability of detection" has been rolled into the "probability of occurrence" rating.

Theoretical Example: ***RPN vs. Expected Cost***

This example uses a standard probability-Occurrence relationship (from Table 4) and a linear cost-Severity relationship (from Table 5). These two tables yield 100 pairs of {probability, cost} and their corresponding {Occurrence, Severity} pair. We can calculate the Risk Priority number (O×S) and expected cost (p×c) for all 100 failure combinations.

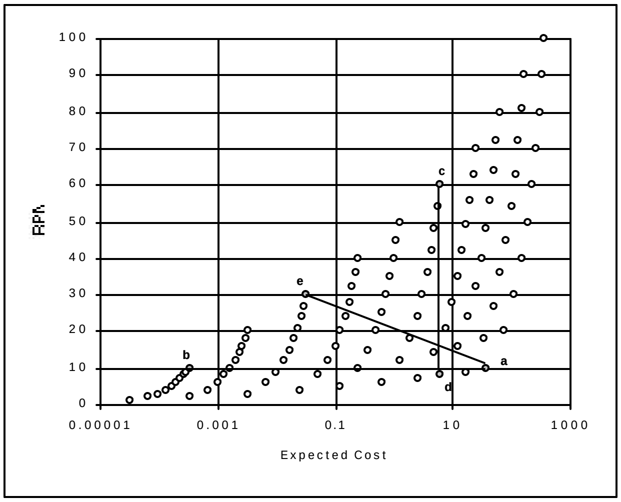

Figure 8 RPN vs. expected cost for 100 pairs of probability and cost

The RPN has a 1-to-many relationship to expected cost (Figure 8); the points don't fall in a monotonically increasing line as we might have expected. The results reveal some interesting facts:

Failures with the same RPN have different expected costs

Points *a* and *b* in Figure 8 depict the wide range of expected costs associated with a single RPN value (Table 6).

Table 6 RPN can have different expected costs

Scenario	Probability	Cost	**Expected cost**	Occurrence Rank, O	Severity Rank, S	**RPN O´S**
a	0.75	$ 50	**$37.50**	10	1	**10**
b	6.66x10^{-7}	$500	**$0.00033**	1	10	**10**

Failures with the same expected cost have different RPNs

For this set of data, an expected cost of $6.25 has a range of RPN from 8 to 60 (Table 7).

Table 7 Expected-cost can have different RPN values

Scenario	Probability	Cost	**Expected cost**	Occurrence Rank, O	Severity Rank, S	**RPN O´S**
d	.125	$50	**$ 6.25**	8	1	**8**
c	.0125	$500	**$ 6.25**	6	10	**60**

Two different RPN priorities would be given to failures with the same expected cost. This situation is shown in Figure 8 by points *c* and *d*.

RPN and expected cost give conflicting priorities

The situation exists where conflicting priorities are given by RPN and expected cost (points *a* and *e* in Figure 7, Table 8).

Table 8 Conflicting priorities of RPN and expected cost

Scenario	Probability	Cost	**Expected cost**	Occurrence Rank, O	Severity Rank, S	**RPN O´S**
a	0.75	$50	**$ 37.50**	10	1	**10**
e	6.66x10-5	$500	**$ 0.033**	3	10	**30**

This could lead to "myopic" decisions when prioritizing risk.

For a linear cost function, we have demonstrated that the Risk Priority Number is an inconsistent measure of risk with respect to expected cost. The two methods will not produce the same risk priorities for a given set of failures. *Using the Detection index will magnify the differences in priorities between expected cost and the RPN.*

4.3 Other Occurrence and Severity Functions

Figure 9 displays expected cost-RPN relationships for nine combinations of Severity-cost relationships (from Table 5) and Occurrence-probability mappings (from Figure 1.)

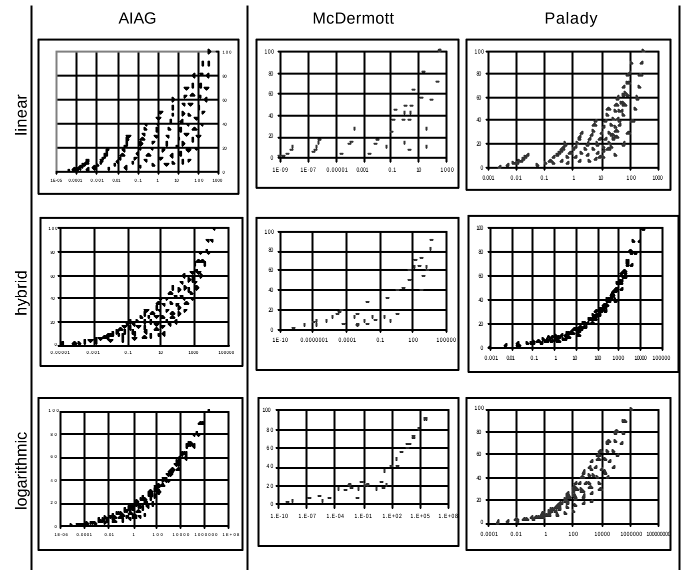

Figure 9 RPN vs. expected cost for several Occurrence-probability & Severity-cost relationships

All combinations result in a 1-to-many relationship between the RPN and expected cost. Ordering risks using the RPN will result in a different priority compared to expected cost for all combinations listed above.

4.4 Example: Hair Dryer

This section compares RPN to expected cost using data from a hand-held hair dryer FMEA. Failure probabilities are listed with a corresponding Occurrence rating. In addition, failure cost estimates are listed with an associated Severity rating (Table 9).

Table 9 RPN and Expected Cost associated with the failure modes of a hair dryer

Scenario	Function/ Requirement	Potential Failure Modes	Potential Causes of Failure	Probability	Occurrence	Local Effects	End Effects	Cost	Severity	exp. Cost	RPN
g	convert power to rotation	no rotation	motor failure	0.001	6	no air flow	hair not dried	100	8	0.1	48
c	convert rotation to flow	no fan rotation	loose fan connection	0.01	8	no air flow	hair not dried	30	6	0.3	48
d	convert power to rotation	no rotation	obstruction impeding fan	1E-04	4	motor overheat	melt casing	1000	9	0.1	36
i	supply power to fan	no power to fan	broken fan switch	0.001	6	no air flow	hair not dried	30	6	0.03	36
j	supply power to fan	no power to fan	loose switch connection	0.001	6	no air flow	hair not dried	30	6	0.03	36
k	supply power to fan	no power to fan	short in power cord	0.001	6	no air flow	hair not dried	30	6	0.03	36
a	convert power to rotation	low rotation	foreign matter-friction	0.1	10	reduced air flow	inefficient drying	10	3	1	30
b	convert power to rotation	no rotation	obstruction impeding fan	0.1	10	no air flow	hair not dried	10	3	1	30
f	supply power to fan	no power to fan	no source power	0.01	8	no air flow	hair not dried	10	3	0.1	24
l	convert power to rotation	low rotation	rotor/stator misalignment	1E-04	4	reduced air flow	hair not dried	30	6	0.003	24
e	supply power to fan	no power to fan	short in power cord	1E-05	2	no air flow	potential injury	10000	10	0.1	20
m	supply power to fan	low power to fan	low source power	1E-04	4	reduced air flow	inefficient drying	10	3	0.001	12
h	convert power to rotation	low rotation	rotor/stator misalignment	0.01	8	noise	noise	5	1	0.05	8

The prioritization given by decreasing expected cost does not match the RPN ordering. Figure 10 shows how the RPN can give lower priority to failures that have high expected cost.

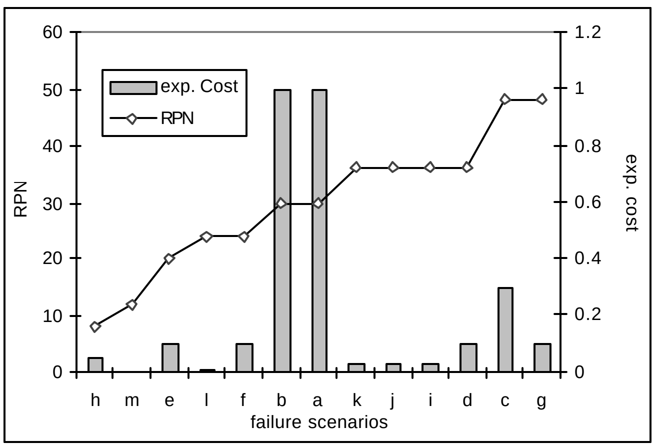

Figure 10 Failures prioritized by expected cost have different priorities than the RPN

Understandably, engineers are not inclined to make probability or cost estimates without any substantiating data. Apparently there is less apprehension with using 1-10 point estimates for probability and severity. However, probability and cost carry more meaning than their RPN counterparts. Both risk criteria are based on educated estimates; the set containing probability and cost contains more information. Additionally, probability and cost are ratio scales, which can be legitimately multiplied into a composite risk measure.

4.5 Other methods of Prioritizing Failures in FMEA

The most popular alternative to the RPN is the "criticality matrix," introduced in the Failure Modes Effects and Criticality Analysis (FMECA) standards (SAE, 1994). The criticality matrix plots probability vs. Severity (Figure 11).

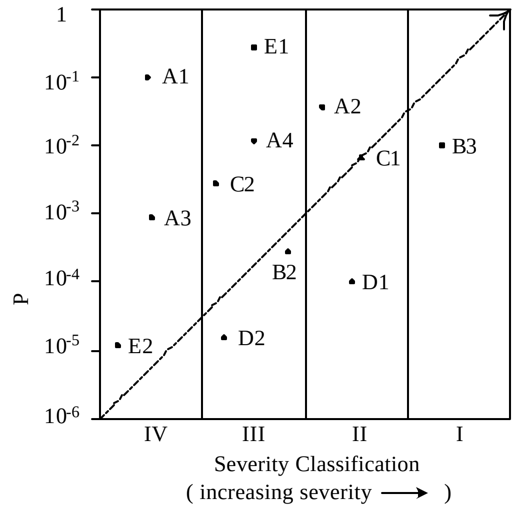

Figure 11 Criticality matrix for prioritizing failures (adapted from Bowles, 1998)

FMECA standards use probability to measure the chance of a failure and plot it on a log scale against severity categories. This technique is preferable to the RPN for the several reasons:

- failure frequency is measured with probability
- the Detection index is eliminated, and
- ordinal measures are not multiplied.

However, the heuristics used to calculate equivalent risk failures are meaningless without knowing the relative magnitude of the Severity classifications. For example, E1, A2, and B3 in Figure 11 are considered "equivalent rank." Depending on the scale of the severity classifications, these points may or may not have equivalent risk priority.

4.6 Using Expected Cost to Make Design Decisions: Projector Bulb Example

Consider a computer video projector used for presentations: bulb failure is a known problem and occurs with probability 0.01. The cost of bulb replacement is $50. The bulb can fail either A) during a presentation or B) while "idle" (i.e., failure without an audience,) with respective probabilities of 0.05 and 0.95. The cost of failure during a presentation is estimated to be $500 more than the $50 cost of replacing the bulb. Expected cost for the two failure scenarios is as follows

I) Current bulb failure rate ($P_{bulb\ failure} = 0.01$)

$$EC_{bulb\ failure} = EC_{presentation}\ (scenario\ A) + EC_{idle}\ (scenario\ B)$$
$$= (P_{bulb\ failure})[(P_{presentation})(\$C_{presentation}) + (P_{idle})(\$C_{idle})]$$
$$= 0.01\ [(0.05)(\$550) + (0.95)(\$50)]$$
$$= \$0.75$$

From here, one can use a decision analytic approach to make design trade-offs. Consider three risk abatement strategies

II) Lower bulb failure rate ($P_{bulb\ failure}$ = 0.005)

$$EC_{reliable\ bulb} = P'_{bulb\ failure}\,[(P_{presentation})(C_{presentation}) + (P_{idle})(C_{idle})]$$
$$= 0.005\,[(0.05)(\$550)) + (0.95)(\$50)]$$
$$= \$0.375$$

III) Lower bulb replacement cost (cost of replacement = $30)

$$EC_{serviceable\ bulb} = P_{bulb\ failure}\ [(P_{presentation})(\$530) + (P_{idle})(C'_{idle})]$$
$$= 0.01\,[(0.05)(\$530) + (0.95)(\$30)]$$
$$= \$0.55$$

IV) Early warning of bulb failure (75% of "in presentation" failures eliminated)

$$EC_{detectable\ bulb} = EC_{presentation} + EC_{idle}$$
$$= P_{bulb\ failure}\,[(P_{presentation})(1-P_{detect})(C_{presentation}) + (P_{detect})(C_{idle})) + (P_{idle})(C_{idle})]$$
$$= 0.01[(0.05)(0.25)(\$550)+[(0.75)(0.05)+(0.95)](\$50)]$$
$$= \$0.5625$$

These calculations are useful for deciding whether to implement specific solutions. Consider that additional product costs for design strategies II, III, and IV are $0.50, $0.15, and $0.10 respectively. We can compare life cycle cost (product cost + failure cost) for the four alternatives (Table 10.)

Table 10 Life cycle cost comparison for design alternatives

Strategy	P_{bulb}	P_{idle}	$P_{presentation}$	C_{idle}	$C_{presentation}$	exp. failure cost	extra cost per unit	life cycle cost
I. current	0.01	0.95	0.05	$50	$550	**$0.75**	$0	**$0.75**
II. reliable bulb	0.005	0.95	0.05	$50	$550	**$0.375**	$0.50	**$0.875**
III. easy to service	0.01	0.95	0.05	$35	$535	**$0.55**	$0.15	**$0.70**
IV. early warning	0.01	0.988	0.013	$50	$550	**$0.563**	$0.10	**$0.663**

The strategies are compared to the current design in Figure 12.

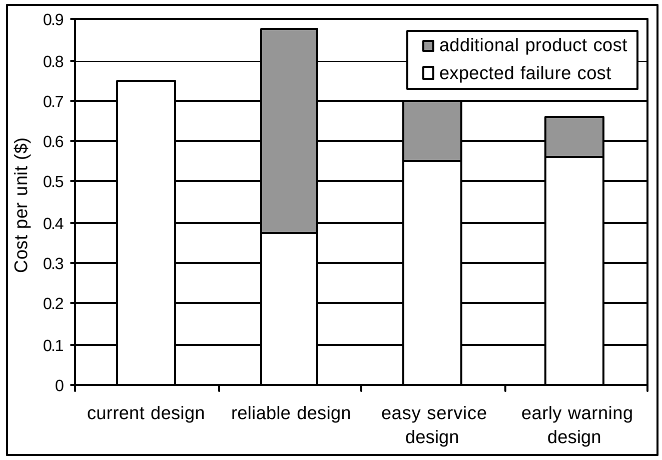

Figure 12 Life cycle cost comparison of design alternatives

By examining both expected failure cost and estimated product cost, the design team can decide which strategy has the lowest overall life cycle cost.

5. CONCLUSIONS AND FUTURE WORK

This paper addressed two major shortcomings of the conventional FMEA: the ambiguous definition of the detection index and the inconsistent RPN scoring scheme. The authors proposed two deployment strategies to improve the effectiveness of FMEA.

1. Organize the FMEA around *failure scenarios* rather than *failure modes*.
2. Evaluate risk using probability and cost.

The method can help attribute cost to failure scenarios and guide design decisions with more precision. Table 11 lists some advantages and disadvantages of scenario-based FMEA and traditional FMEA.

Table 11 Comparison of scenario-based & Traditional FMEA

Scenario-based FMEA using expected cost	Traditional FMEA using the Risk Priority Number
disadvantages	**disadvantages**
cost and probability are difficult to estimate without data	O, S, D values do not have meaning, definitions vary
there is some aversion to using probability and cost estimates	Multiplication of ordinal scales is not valid
advantages	**advantages**
probability and cost have universal meaning, consistent definitions	1-10 scales are familiar and "quick"
rules for manipulating probabilities are well established - sub-system FMEA using probability can be more easily integrated into system FMEA	there is a large existing base of FMEA software and procedures that use the RPN
estimated ratio scales contain more information than estimated ordinal scales	
FMEA can be used for cost-based decisions	
using standard metrics facilitates sharing of FMEA data	
can incorporate uncertainty into probability and costs	
costs can reflect the concept of utility theory	

The examples in this paper have been using deterministic point-estimates for probability and cost. There is an opportunity to include uncertainty into the estimates of the cost and probability parameters. Without detailed information, using a range of probability and cost estimates is favorable to using point-estimates. In addition, a more formal procedure could be used to trace causal chains and their probabilities, such as Bayesian Nets (Lee, 1999).

Our future challenges include: a) Validation of the utility of scenario-based FMEA through more case studies, and b) Using the cost-based evaluation of failure scenarios to the simultaneous design of hardware, monitoring and controls, and service logistics. The second topic presents an enormous challenge and opportunity as more companies provide long-term service support as a business strategy. For example, aircraft engine manufacturers are now leasing engines rather than selling, i.e., providing customers with "thrust" as opposed to just hardware. Such a business strategy requires an effective means of managing the life-cycle costs of the system by balancing failure cost (risk) and long term maintenance cost against up-front product cost. The authors firmly believe that scenario-based FMEA will assist in the design challenges of long-term support of complex products.

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REFERENCES

Aerospace Recommended Practice ARP926A, (1979).

Automotive Industry Action Group (1995) *Potential Failure Modes and Effects Analysis (FMEA) Reference Manual*, Detroit, MI.

Bowles, J. (1998) "The New SAE FMECA Standard," *Proceedings of the 1998 IEEE Annual Reliability and Maintainability Symposium*, pp. 48-53.

Di Marco, P., C. Eubanks and K. Ishii (1995), "Service Modes and Effect Analysis: Integration of Failure Analysis and Serviceability Design," *Proc. of the 15th Annual International Computers in Engineering Conference*, Boston, MA, pp. 833-840.

Ford Motor Company (1988) "Potential Failure Modes and Effects Analysis in Design and for Manufacturing and Assembly Processes Instruction Manual," Sept. 1988.

Gilchrist, W. (1993) "Modeling failure modes and effects *International Journal of Quality and Reliability Management*, 10(5), 16-23.

Hauptmanns, U., and W. Werner (1991) *Engineering Risks: Evaluation and Valuation*, Springer-Verlag New York, Inc., March 1991.

Humphries, N., (1994) *Murphy's Law Overruled: FMEA in Design, Manufacture and Service*, B&N Humphries Learning Service Pty Ltd, Victoria, Australia.

Kaplan, S. and B.J. Garrick (1981) "On the Quantitative Definition of Risk," *Risk Analysis*, 1(1) pp. 11-27.

Lee, B.H. (1999) "Design FMEA for Mechatronic Systems Using Bayesian Network Causal Models," *ASME Design Engineering Technical Conference*, Las Vegas, NV.

Lindley, D.V. (1965) *Introduction to Probability and Statistics from a Bayesian Viewpoint*, 2 Volumes, Cambridge Press, Cambridge.

McDermott, R. E., Mikulak, R. J., and Beauregard, M. R. (1996) *The basics of FMEA*, New York: Quality Resources.

Modarres, M. (1992) *What Every Engineer Should Know about Reliability and Risk Analysis*, Marcel Dekker, Inc., New York, NY.

Morgan, M. G., and M. Henrion (1990) *Uncertainty: A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis*, Cambridge Press, 1990.

Palady, P. (1995) *Failure Modes and Effects Analysis: Predicting & Preventing Problems Before They Occur*, PT Publications, West Palm Beach, FL, 1995.

Rasmussen, N.C. (1981) "The Application of Probabilistic Risk Assessment Techniques to Energy Technologies," *Prog. Energy Combust. Sci.*, 6, pp. 123-138.

Society of Automotive Engineers (SAE) (1994), "Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)

Reference Manual", Surface Vehicle Recommended Practice J1739, July 1994.

Stamatis, D.H., (1995) *Failure Mode and Effect Analysis: FMEA from Theory to Execution*, ASQC Quality Press, Milwaukee, WI.

United States Department of Defense (USDoD) (1974/80/84), "Procedures for Performing A Failure Mode, Effects and Criticality Analysis", US MIL-STD-1629(ships), November 1974, US MIL-STD-1629A, November 1980, US MIL-STD-1629A/Notice 2, November 1984, Washington, DC.

Voetter, M. and T. Mashhour (1996) "Verbesserung der FMEA durch eine Systematische Erfassung von Kausal-zusammenhaengen", VDI-Z 138, Heft 4.

Webster's II New Riverside University Dictionary (1988) Houghton Mifflin, Boston, MA, p. 1013.