Scenario-based FMEA
Using Expected Cost

A New Perspective on Evaluating Risk in FMEA

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Failure Modes & Effects Analysis

FMEA is a technique used to identify, prioritize, and eliminate potential failures from the system, design or process before they reach the customer

– Omdahl, 1988

FMEA is a risk management tool used on Products (designs) and Processes
# Three Phases of FMEA

<table>
<thead>
<tr>
<th>Phase</th>
<th>Question</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Identify</strong></td>
<td>• What can go wrong?</td>
<td><strong>Failure Descriptions</strong>&lt;br&gt;Causes → Failure Modes → Effects</td>
</tr>
<tr>
<td><strong>Analyze</strong></td>
<td>• How likely is a failure?&lt;br&gt;• What are the consequences?</td>
<td><strong>Risk Priority Number</strong>&lt;br&gt;( RPN = O \times S \times D )</td>
</tr>
<tr>
<td><strong>Act</strong></td>
<td>• What can be done?&lt;br&gt;• How can we eliminate the cause?&lt;br&gt;• How can we reduce the severity?</td>
<td>• Design solutions,&lt;br&gt;• test plans,&lt;br&gt;• manufacturing changes,&lt;br&gt;• error proofing, etc.</td>
</tr>
</tbody>
</table>
History of FMEA

- First used in the 1960’s in the Aerospace industry during the Apollo missions
- In 1974, the Navy developed FMEA Procedure Mil-Std-1629
- In the early 1980’s, troubled US automotive companies began to incorporate FMEA into their product development process
- Mil-Std 1629A is the most widely used FMEA procedure

FMEA Spreadsheet

<table>
<thead>
<tr>
<th>Function or Requirement</th>
<th>Potential Failure Modes</th>
<th>Potential Causes of Failure</th>
<th>Occurrence</th>
<th>Local Effects</th>
<th>End Effects on Product, User, Other Systems</th>
<th>Severity</th>
<th>Detection Method/Current Controls</th>
<th>Detection RPN</th>
<th>Actions Recommended to Reduce RPN</th>
<th>Responsibility and Target Completion Date</th>
</tr>
</thead>
</table>

FMEA and the Risk Priority Number (RPN) have been around for many years
Criticisms of FMEA

- FMEA often misses key failures (Bednarz et al., 1988)
- FMEA performed too late does not affect key product/process decisions (McKinney, 1991)
- The FMEA Process is tedious (Ormsby et al., 1992)
- The Risk Priority Number is not a good measure of Risk (Gilchrist, 1993: Harpster 1999)

Let’s discuss the RPN as a measure of Risk
The Risk Priority Number

- The RPN is used *prioritize* potential failures

\[ RPN = (\text{Occurrence}) \times (\text{Severity}) \times (\text{Detection}) \]

- **Occurrence (O):** How likely is the *cause and failure mode* to occur?

- **Severity (S):** How serious is the impact of the *end effect*?

- **Detection (D):** How difficult is the *cause and failure mode* to detect?

*O, S, and D are rated on a 1 to 10 scale*
Occurrence is Related to Probability

Ratings arbitrarily reflect probabilities
Severity is Related to "Cost"

Cost-Severity relationships for hypothetical industries
Criticisms of Detection

• “Detection” has many definitions

• Most definitions are confusing since they address:
  - design review process (an organizational issue)
  - manufacturing inspection (a QC issue)
  - the diagnosibility of a failure (a Severity issue)

• High cost (time), for low benefit

• Some standards ignore Detection (SAE J1739)

Our ultimate interest: How likely is the failure to occur?
No Consistent Definition of Terms

- Definitions for O, S, D depend on FMEA standard
- O, S, D and RPN can have different meanings for each FMEA
- Sharing numbers between companies and groups is very difficult

RPN number has no clear “meaning”
O, S, D use Ordinal Scales

- Used to rank items along a single dimension (e.g. hotels)
- Ordinal scales preserve transitivity (rank-order)
- Magnitudes of Ordinal scales are “not meaningful”
  - 8 is not twice as much as 4
- RPN is the product three ordinal indices
- But multiplication of ordinal indices is not “valid”, since the product does not preserve rank-order
What is Risk?

- **Possibility of incurring damage** (Hauptmanns & Werner, 1991)
- **Exposure to chance of injury or loss** (Morgan & Henrion, 1988)
- **Possibility of loss** or injury (Webster’s Dictionary, 1998)

**Elements of risk: “chance” and “loss”**

- **Probability** is a universal measure of **chance**
- **Cost** is an accepted measure of **loss**
- Most common measure of risk is “Expected Cost”

\[
\text{Expected Cost} = (\text{probability}) \times (\text{cost})
\]
### RPN vs. Expected Cost Example

#### Example Occurrence Ratings

<table>
<thead>
<tr>
<th>Occurrence</th>
<th>Probability (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.667 E-7</td>
</tr>
<tr>
<td>2</td>
<td>6.667 E-6</td>
</tr>
<tr>
<td>3</td>
<td>6.667 E-5</td>
</tr>
<tr>
<td>4</td>
<td>0.0005</td>
</tr>
<tr>
<td>5</td>
<td>0.0025</td>
</tr>
<tr>
<td>6</td>
<td>0.0125</td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
</tr>
<tr>
<td>8</td>
<td>0.125</td>
</tr>
<tr>
<td>9</td>
<td>0.333</td>
</tr>
<tr>
<td>10</td>
<td>0.75</td>
</tr>
</tbody>
</table>

#### Example Cost Function

<table>
<thead>
<tr>
<th>Severity</th>
<th>Cost (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>350</td>
</tr>
<tr>
<td>8</td>
<td>400</td>
</tr>
<tr>
<td>9</td>
<td>450</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exp. RPN Cost (OxS) (pxc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
</tr>
<tr>
<td>32</td>
</tr>
</tbody>
</table>

- 100 possible failure “ratings” (Assume Detection = 1)
- We can plot RPN vs. Expected Cost
What Relationship Do We Expect?

We expect a monotonically increasing relationship

What is the actual relationship?
RPN vs. Expected Cost

RPN-Expected cost mapping is not 1 to 1
Constant Exp. Cost has Wide range of RPN’s

\[ \text{EC} = \$6.25 \]
\[ \text{RPN} = 8 \text{ to } 60 \]
Constant RPN has Wide Range of ECost

\[ RPN = 10 \]

\[ EC = $0.0003 \text{ to }$37 \]

<table>
<thead>
<tr>
<th>Probability</th>
<th>Cost</th>
<th>Expected cost</th>
<th>Occurrence Rank, L</th>
<th>Severity Rank, S</th>
<th>RPN * ((O \times S \times D))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>$50</td>
<td>$37.50</td>
<td>10</td>
<td>1</td>
<td>10 * (0.75 \times 10 \times 1)</td>
</tr>
<tr>
<td>6.66 \times 10^{-7}</td>
<td>$500</td>
<td>$0.00033</td>
<td>1</td>
<td>10</td>
<td>10 * (6.66 \times 10^{-7} \times 1 \times 10)</td>
</tr>
</tbody>
</table>
Higher RPN can Have **Lower** ECost

<table>
<thead>
<tr>
<th>Probability</th>
<th>Cost</th>
<th>Expected cost</th>
<th>Occurrence Rank, O</th>
<th>Severity Rank, S</th>
<th>RPN <em>(O x S x D)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.75</td>
<td>$50</td>
<td>$37.50</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>6.66x10^-5</td>
<td>$500</td>
<td>$0.033</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

**b** has **higher** RPN priority than **a** but **lower** expected cost.
RPN Priority Differs from Exp Cost

Using “Detection” makes RPN-EC correlation worse
Conventional Failure Mode Representation

Potential 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 one lower level effect. (AIAG)

- Sometimes failure mode is a cause, sometimes an effect
  ...
  \[\rightarrow\] Confusing

- Conventional FMEA do not always differentiate between “failure modes” with different outcomes
  - Stage of detection is not specified...
  - Risk estimates are grouped & mitigation strategies are unclear
Failure Scenarios

- A failure scenario is an undesired cause-effect chain of events.
- The use of failure scenarios helps with failure representation and risk evaluation.
Failure Scenarios

- Scenarios have different probabilities and consequences

**Scenario 1: probability 1, consequence 1**

Grease fire → Kitchen fire

- Immediate effect 1
- Next-level effect 1
- End effect 1

- Alarm works → Kitchen damage
- Alarm fails → Building damage

**Scenario 2: probability 2, consequence 2**

- Conventional FMEA might list as one Failure Mode & one RPN Rating
Traditional Failure “Modes”

Design
- design flaw
- prototype testing

Manufacturing
- fabrication / assembly flaw
- manufacturing inspection

Shipping & Installation
- shipping installation
- operation

Operation
- field failure

Occurrence - failure (cause) introduced
Detection - failure (effect) discovered
Severity

RPN = O x S x D
Life Cycle Failure Scenarios

- failure (cause) introduced
- failure (effect) discovered
Generating Failure Scenarios

Function-Structure Map for Hair Dryer

Failure modes

local effects

end effects

Dry Hair

provid airflow

heat air

provide user interface

provide airflow

convert electric to rotation

convert rotation to flow

support flow generation

supply air

supply electricity

convert electric to heat

control flow

control temperature

convey flow

transfer heat to air

provide handle

provide controls

protect user

provide electricity

supply electricity

convert electric to heat

control flow

control temperature

convey flow

support flow generation

provide electricity

local effects

end effects

ambient air

switch

fan housing

motor

fan blade

heating element

springs

thermocouple

temperature switch

heat shield

front grid

front case

power cord

switch actuator

rear housing

screen

ground wire

power source

Hair Dryer

causes

Failure modes

Hair Dryer
Example: Hair Dryer FMEA

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Function/ Requirement</th>
<th>Potential Failure Modes</th>
<th>Potential Causes of Failure</th>
<th>Probability</th>
<th>Occurrence</th>
<th>Local Effects</th>
<th>End Effects on Product, User, Other Systems</th>
<th>Cost</th>
<th>Severity</th>
<th>Detection</th>
<th>exp Cost</th>
<th>RPN</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>convert electric power to rotation</td>
<td>no rotation</td>
<td>motor failure</td>
<td>0.001</td>
<td>6</td>
<td>no air flow</td>
<td>hair not dried</td>
<td>100</td>
<td>8</td>
<td>1</td>
<td>0.1</td>
<td>48</td>
</tr>
<tr>
<td>c</td>
<td>convert rotation to flow</td>
<td>no fan rotation</td>
<td>loose or worn fan connection to rotor</td>
<td>0.01</td>
<td>8</td>
<td>no air flow</td>
<td>hair not dried</td>
<td>30</td>
<td>6</td>
<td>1</td>
<td>0.3</td>
<td>48</td>
</tr>
<tr>
<td>d</td>
<td>convert electric power to rotation</td>
<td>no rotation</td>
<td>obstruction impeding fan</td>
<td>0.0001</td>
<td>4</td>
<td>motor overheat</td>
<td>melt casing</td>
<td>1000</td>
<td>9</td>
<td>1</td>
<td>0.1</td>
<td>36</td>
</tr>
<tr>
<td>i</td>
<td>supply electricity to fan</td>
<td>no electricity to fan motor</td>
<td>broken fan switch</td>
<td>0.001</td>
<td>6</td>
<td>no air flow</td>
<td>hair not dried</td>
<td>30</td>
<td>6</td>
<td>1</td>
<td>0.03</td>
<td>36</td>
</tr>
<tr>
<td>j</td>
<td>supply electricity to fan</td>
<td>no electricity to fan motor</td>
<td>loose switch connection</td>
<td>0.001</td>
<td>6</td>
<td>no air flow</td>
<td>hair not dried</td>
<td>30</td>
<td>6</td>
<td>1</td>
<td>0.03</td>
<td>36</td>
</tr>
<tr>
<td>k</td>
<td>supply electricity to fan</td>
<td>no electricity to fan motor</td>
<td>short in power cord</td>
<td>0.001</td>
<td>6</td>
<td>no air flow</td>
<td>hair not dried</td>
<td>30</td>
<td>6</td>
<td>1</td>
<td>0.03</td>
<td>36</td>
</tr>
<tr>
<td>a</td>
<td>convert electric power to rotation</td>
<td>low rotation</td>
<td>hair/foreign matter increasing friction</td>
<td>0.1</td>
<td>10</td>
<td>reduced air flow</td>
<td>inefficient drying</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>b</td>
<td>convert electric power to rotation</td>
<td>no rotation</td>
<td>obstruction impeding fan</td>
<td>0.1</td>
<td>10</td>
<td>no air flow</td>
<td>hair not dried</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>f</td>
<td>supply electricity to fan</td>
<td>no electricity to fan motor</td>
<td>no source power</td>
<td>0.01</td>
<td>8</td>
<td>no air flow</td>
<td>hair not dried</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>0.1</td>
<td>24</td>
</tr>
<tr>
<td>l</td>
<td>convert electric power to rotation</td>
<td>low rotation</td>
<td>rotor/stator misalignment</td>
<td>0.0001</td>
<td>4</td>
<td>reduced air flow</td>
<td>hair not dried</td>
<td>30</td>
<td>6</td>
<td>1</td>
<td>0.003</td>
<td>24</td>
</tr>
<tr>
<td>e</td>
<td>supply electricity to fan</td>
<td>no electricity to fan motor</td>
<td>short in power cord</td>
<td>0.00001</td>
<td>2</td>
<td>no air flow</td>
<td>potential user injury</td>
<td>10000</td>
<td>10</td>
<td>1</td>
<td>0.1</td>
<td>20</td>
</tr>
<tr>
<td>m</td>
<td>supply electricity to fan</td>
<td>low current to fan motor</td>
<td>low source power</td>
<td>0.0001</td>
<td>4</td>
<td>reduced air flow</td>
<td>inefficient drying</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>0.001</td>
<td>12</td>
</tr>
<tr>
<td>h</td>
<td>convert electric power to rotation</td>
<td>low rotation</td>
<td>rotor/stator misalignment</td>
<td>0.01</td>
<td>8</td>
<td>noise generation</td>
<td>noise generation</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0.05</td>
<td>8</td>
</tr>
</tbody>
</table>

- 13 scenarios rated for probability/ cost, Severity/ Occurrence
Example: Hair Dryer FMEA

RPN gives different priority than expected cost
Deployment of Expected Cost in FMEA

- Relate ranges of probability and cost to a general scale

<table>
<thead>
<tr>
<th>Probability</th>
<th>from</th>
<th>to</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL</td>
<td>0</td>
<td>10e-5</td>
</tr>
<tr>
<td>L</td>
<td>10e-5</td>
<td>0.001</td>
</tr>
<tr>
<td>M</td>
<td>0.001</td>
<td>0.01</td>
</tr>
<tr>
<td>H</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>VH</td>
<td>0.1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost</th>
<th>from</th>
<th>to</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>L</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>M</td>
<td>500</td>
<td>5,000</td>
</tr>
<tr>
<td>H</td>
<td>5,000</td>
<td>50,000</td>
</tr>
<tr>
<td>VH</td>
<td>&gt;50,000</td>
<td>-</td>
</tr>
</tbody>
</table>

Example:

Prob. = Low  
Cost = Medium  

\[ \text{Example:} \]

\[ \text{Prob. = Low} \]
\[ \text{Cost = Medium} \]

\[ = \frac{(10e-5 + 0.001) \times (500 + 5000)}{2} \]
\[ = \frac{1.01 \times 5500}{2} \]
\[ = 1.39 \]

Once tables & ranges are defined, one can use:
(estimated probability) \times (estimated cost)
Another Expected Cost Strategy

- Estimate probability range (low, nominal, high)
- Estimate failure cost (low, nominal, high)
- Calculate expected cost distribution
- Rank risks according to mean expected cost

<table>
<thead>
<tr>
<th>Prob.</th>
<th>cost</th>
<th>ECost</th>
</tr>
</thead>
<tbody>
<tr>
<td>.001</td>
<td>.01</td>
<td>200</td>
</tr>
<tr>
<td>.01</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
<td>1.375</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Failure Scenario A

<table>
<thead>
<tr>
<th>Prob.</th>
<th>cost</th>
<th>ECost</th>
</tr>
</thead>
<tbody>
<tr>
<td>.0001</td>
<td>.001</td>
<td>500</td>
</tr>
<tr>
<td>.001</td>
<td>500</td>
<td>4000</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>1.24</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Failure Scenario B
Challenges

- Cost & probability data is difficult to estimate w/o data
- There is some aversion to using probability and cost estimates
- 1-10 scales for Occurrence, Detection, & Severity is familiar and “quick”
- Many FMEA standards and software use RPN

*RPN is the industry standard for FMEA*
Advantages

• Analyze Failure Modes by Life-cycle “Scenarios”
  – Clarifies the cause / end-effect relationship
  – Takes the ambiguous “Detection” out of the picture

• Expected cost is an accepted measure of risk
  – Cost and probability terms are consistent
  – Expected cost ties FMEA to $$

• Engineers can compare failure costs to solution cost to minimize life cycle costs
  – Reliability vs. serviceability vs. better diagnostics

Using Expected cost in scenario-based FMEA presents a more useful representation & evaluation of “risk”
Concluding Remarks

Applications & Workshops

- Training Workshops given at GE CR&D, Toshiba 6 sigma
- Integral part of Stanford’s graduate dfM curriculum (me217.stanford.edu)
- On-going research project: Design & costing of next linear collider (Stanford/SLAC project)

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Questions??