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

Phase	***Question***	***Output***
Identify	• What can go wrong?	**Failure Descriptions** Causes → Failure Modes → Effects
Analyze	• How likely is a failure? • What are the consequences?	**R**isk **P**riority **N**umber (**RPN** = **O**ccurrence × **S**everity × **D**etection)
Act	• What can be done? • How can we eliminate the cause? • How can we reduce the severity?	• Design solutions, • test plans, • manufacturing changes, • error proofing, etc.

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

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

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 = (Occurrence) x (Severity) x (Detection)

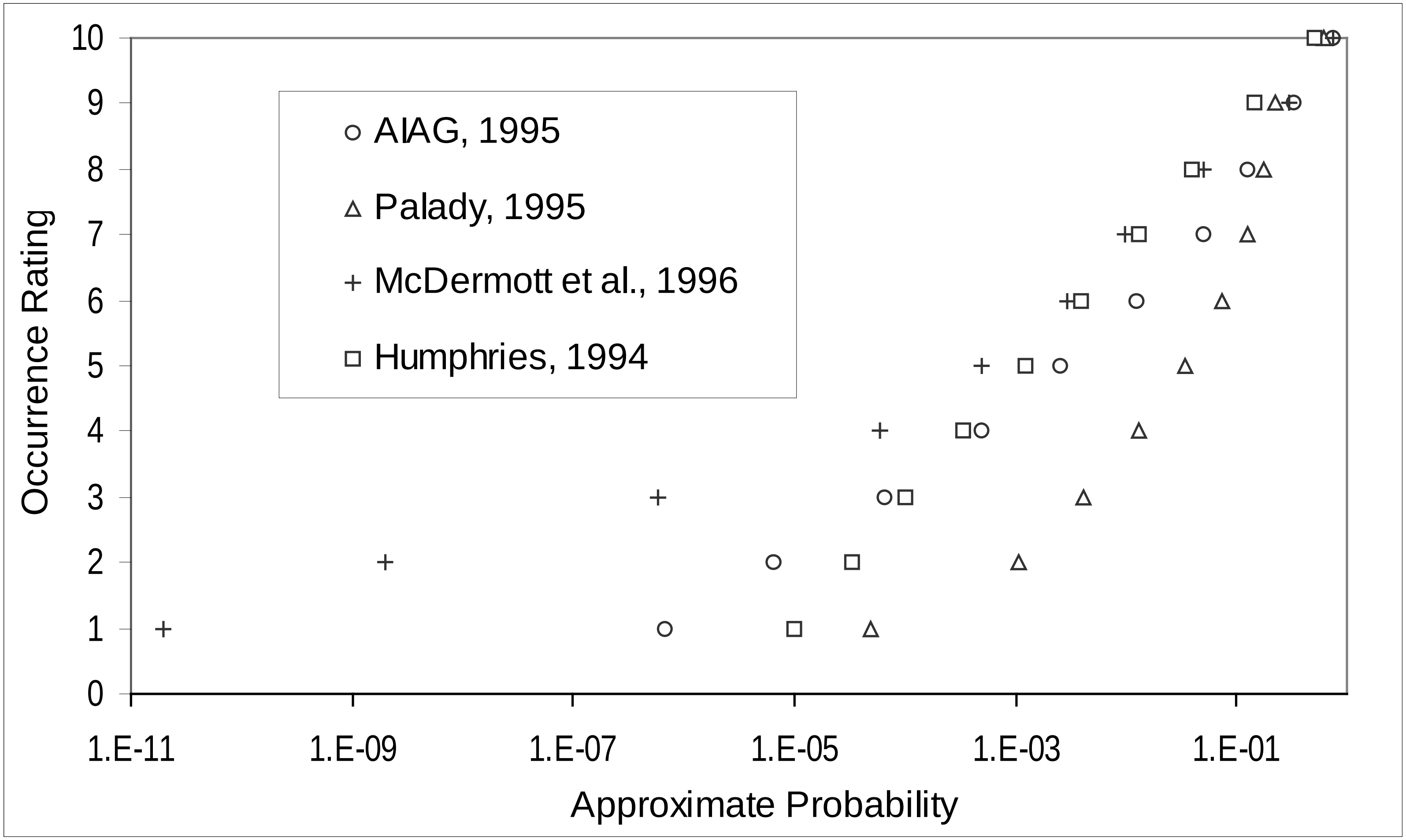
- **Occurrence (O)**: How likely is the **cause and failure mode** to occur?

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

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

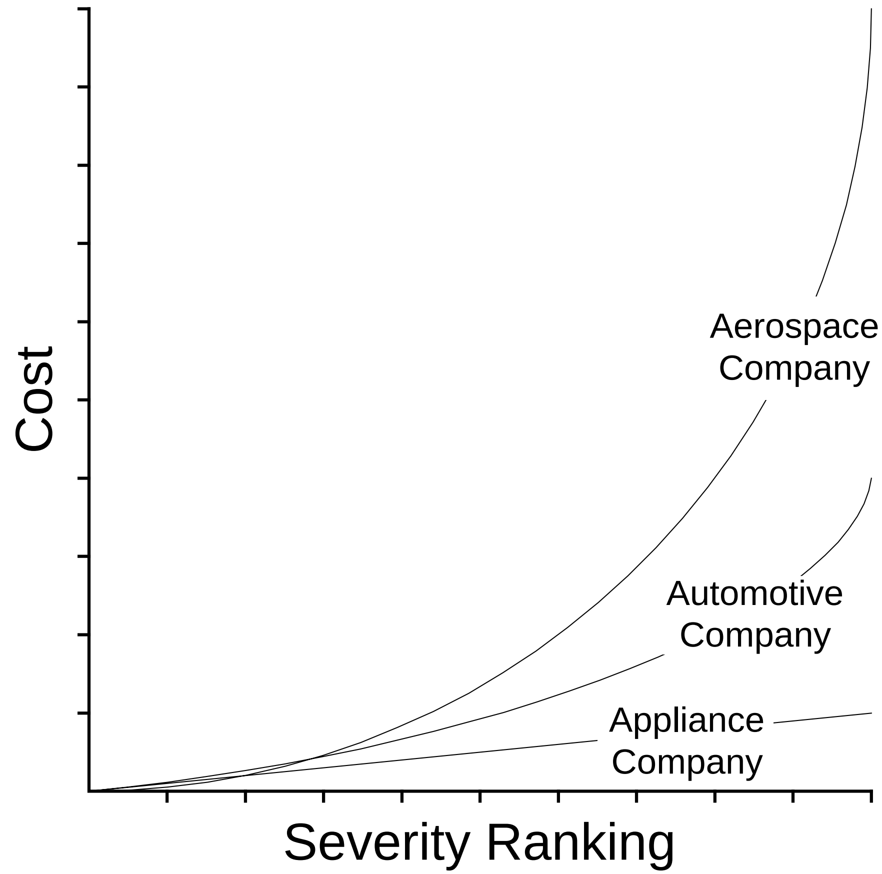
O, S, and D are rated on a 1 to 10 scale

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

Occurrence	probability (p)
1	6.667 E-7
2	6.667 E-6
3	6.667 E-5
4	0.0005
5	0.0025
6	0.0125
7	0.05
8	0.125
9	0.333
10	0.75

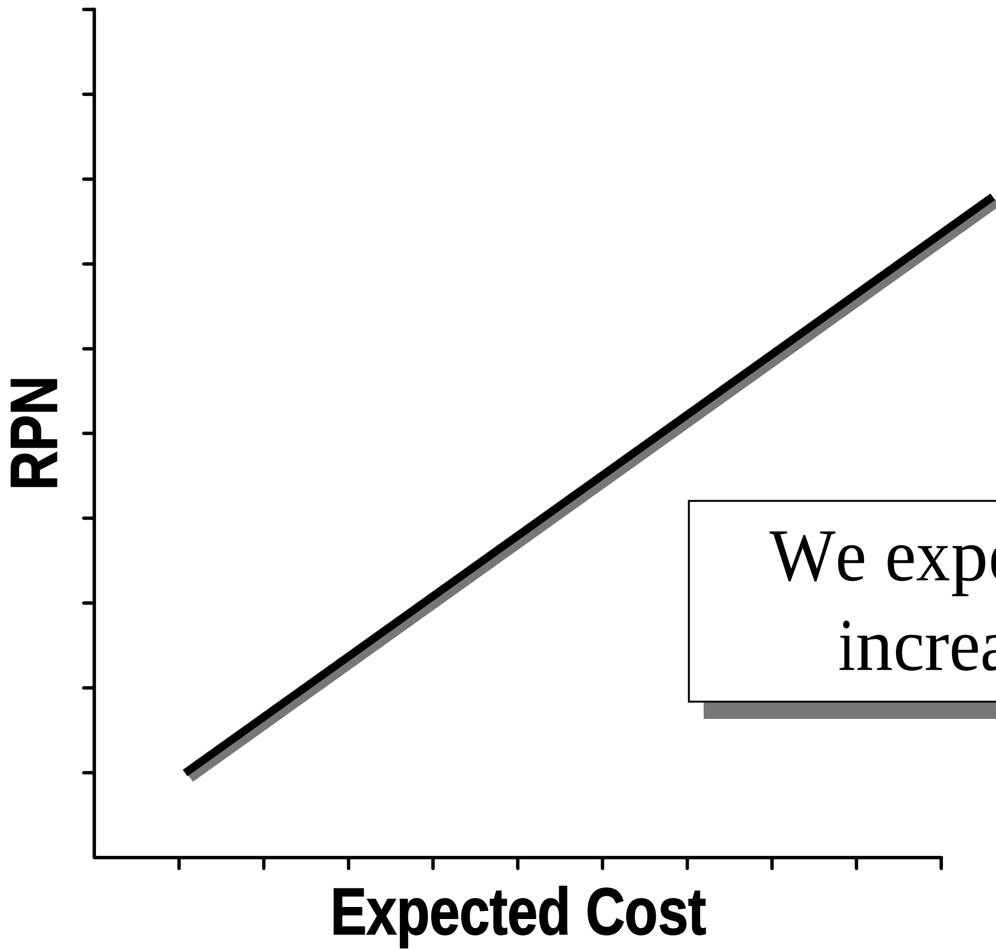
Example Cost Function

Severity	cost (c)
1	50
2	100
3	150
4	200
5	250
6	300
7	350
8	400
9	450
10	500

RPN (OxS)	Exp. Cost (pxc)
40	$31
32	$0.2

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

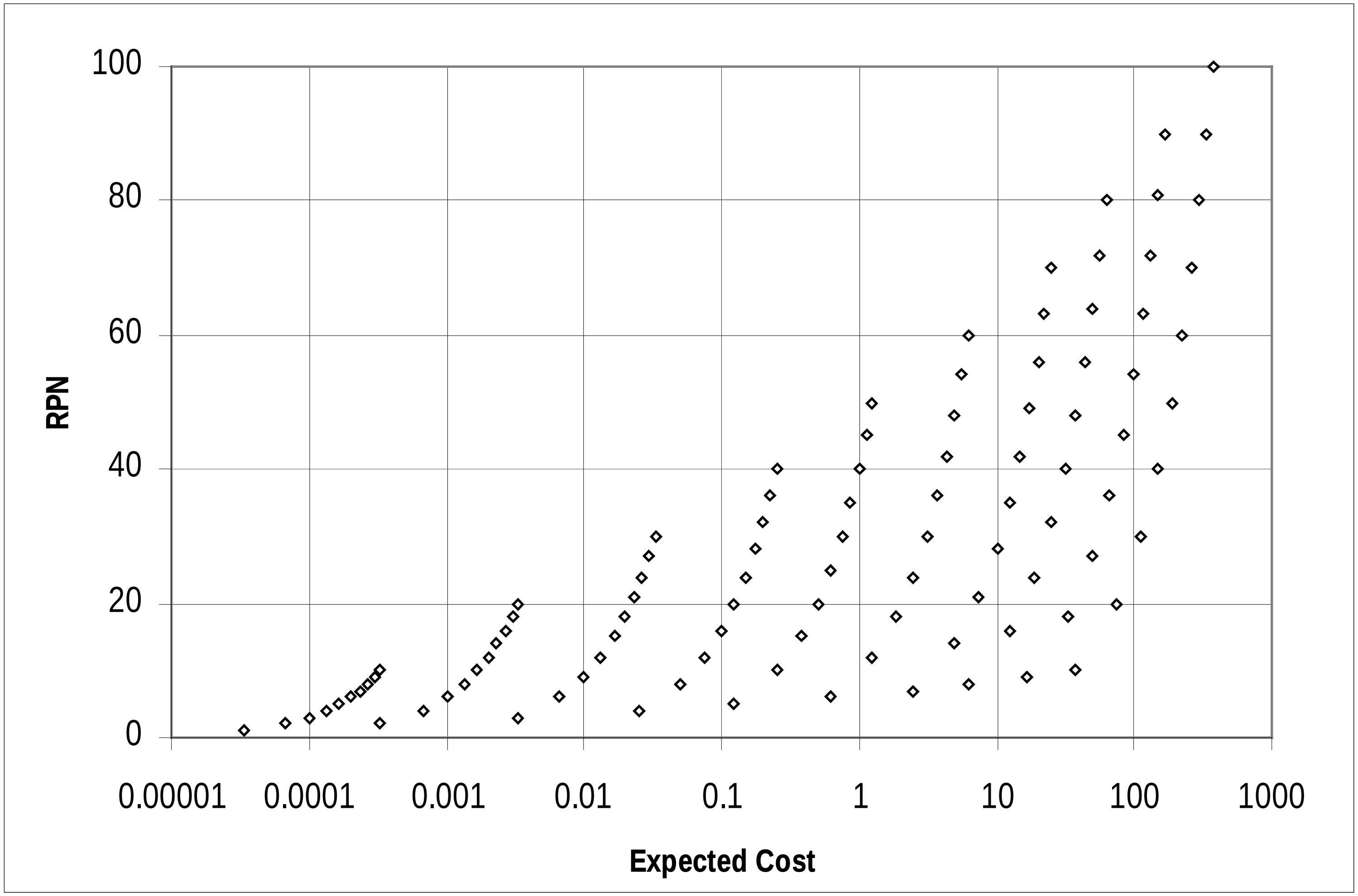
What Relationship Do We Expect?



We expect a monotonically increasing relationship

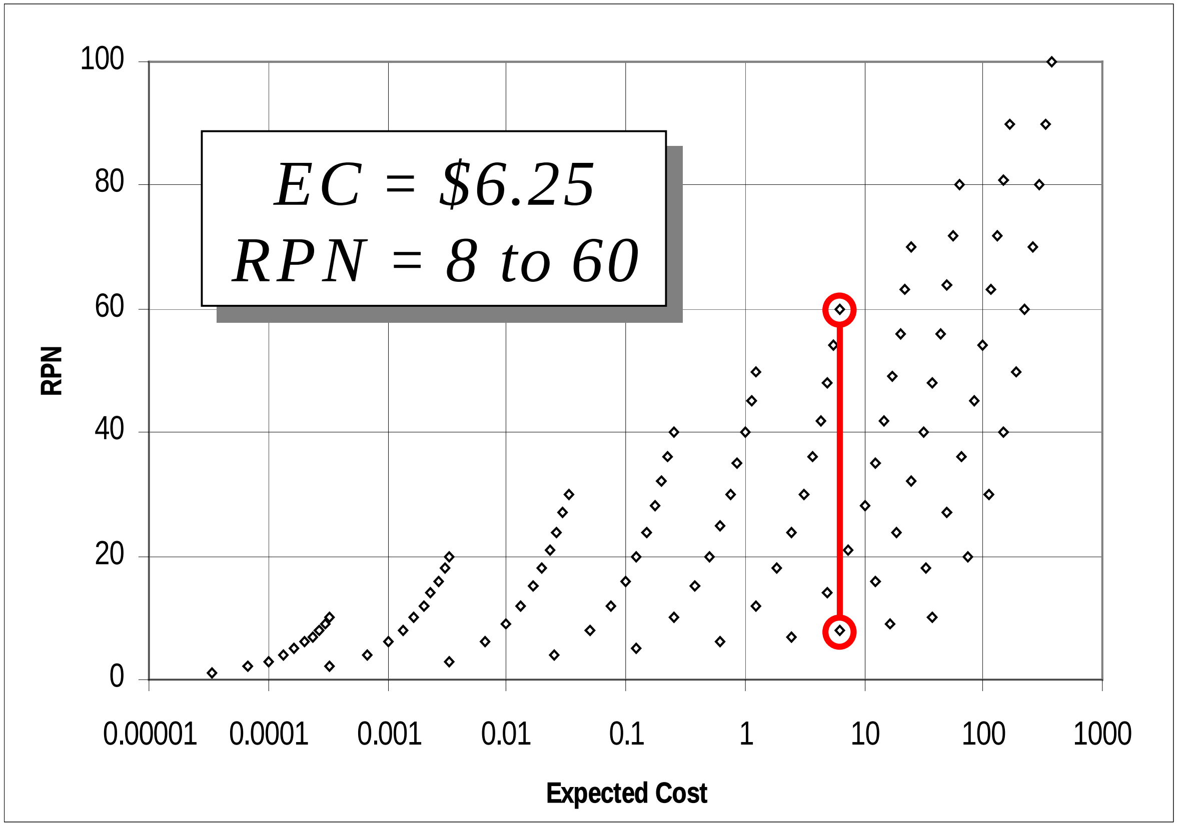
What is the actual relationship ?

RPN vs. Expected Cost



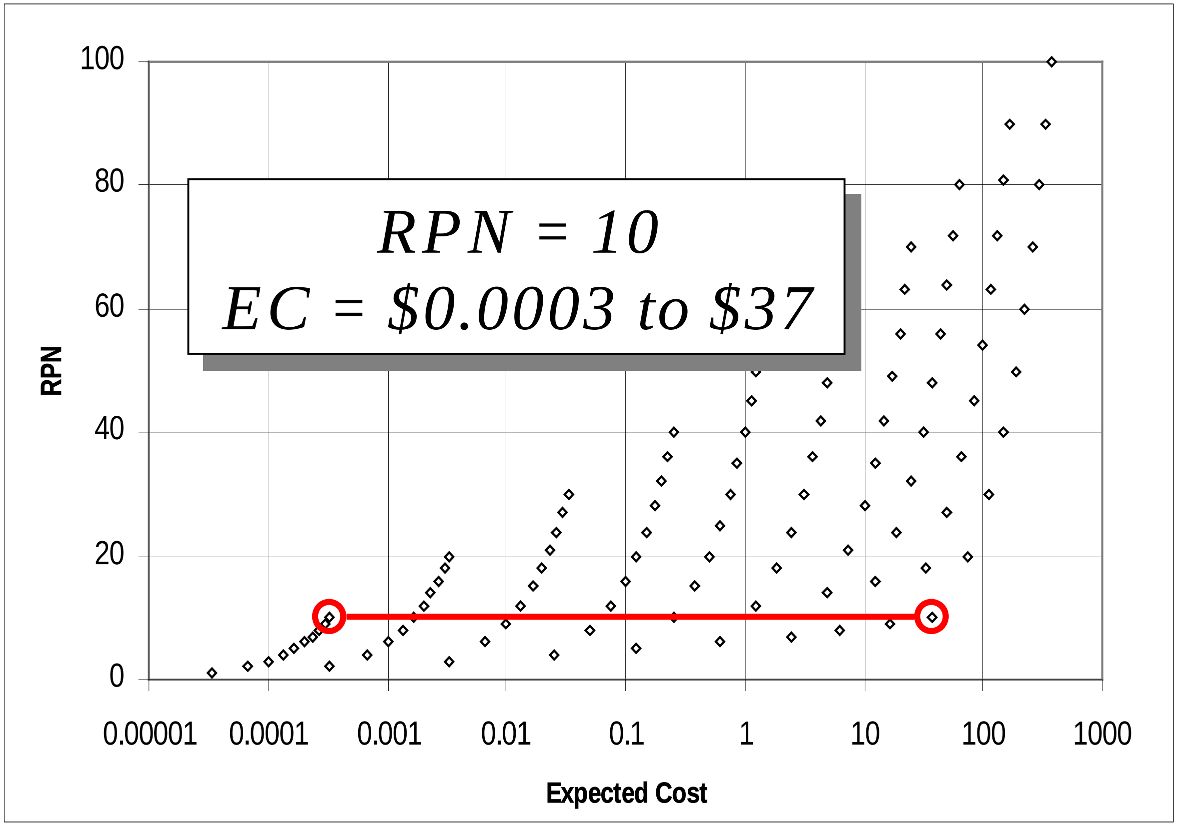
RPN-Expected cost mapping is not 1 to 1

Constant Exp. Cost has Wide range of RPN's



Probability	Cost	Expected cost	Occurrence Rank, L	Severity Rank, S	RPN * (O x S x D)
.125	$50	$ 6.25	8	1	8
.0125	$500	$ 6.25	6	10	60

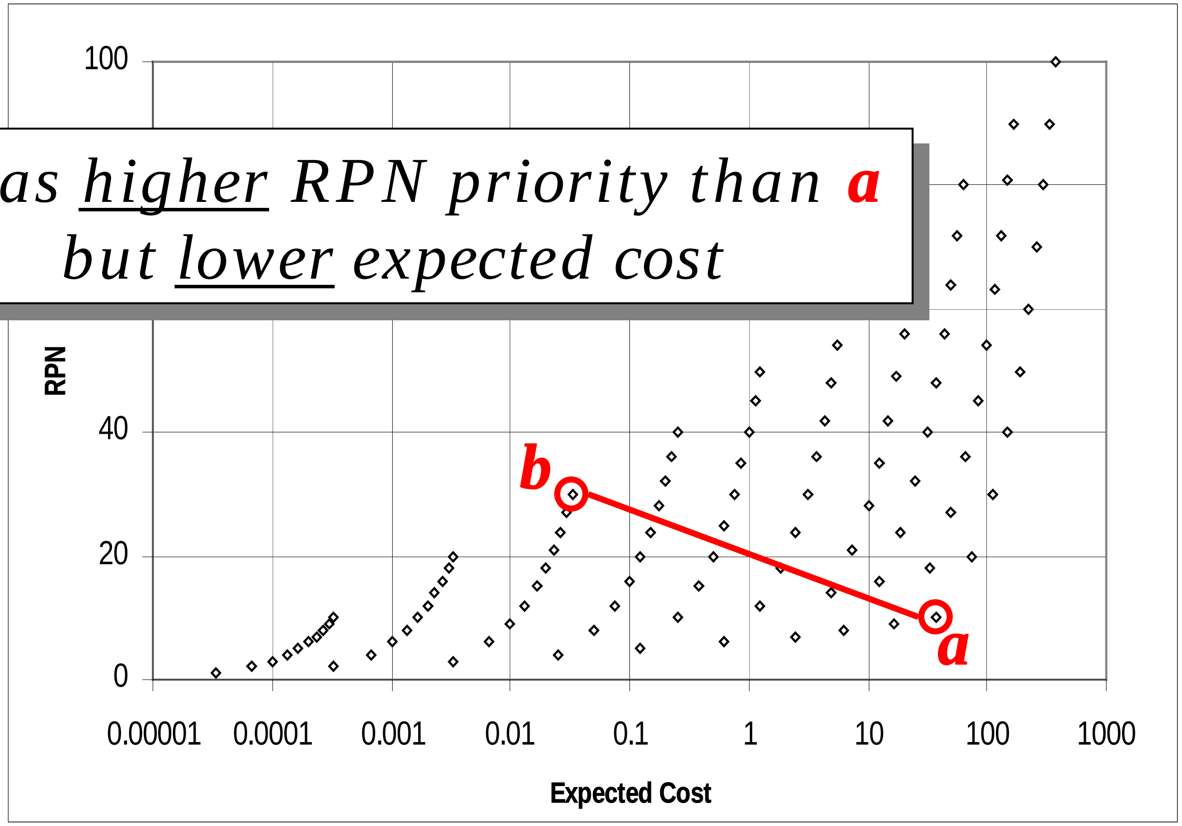
Constant RPN has Wide Range of ECost



Probability	Cost	Expected cost	Occurrence Rank, L	Severity Rank, S	RPN * (O x S x D)
0.75	$ 50	$ 37.50	10	1	10
6.66x10-7	$500	$ 0.00033	1	10	10

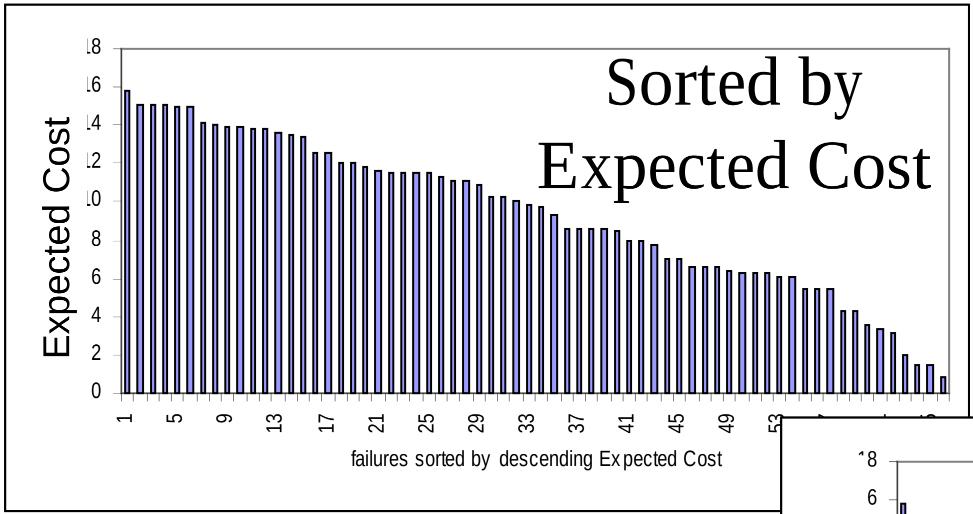
Higher RPN can Have Lower ECost

***b** has higher RPN priority than **a** but lower expected cost*

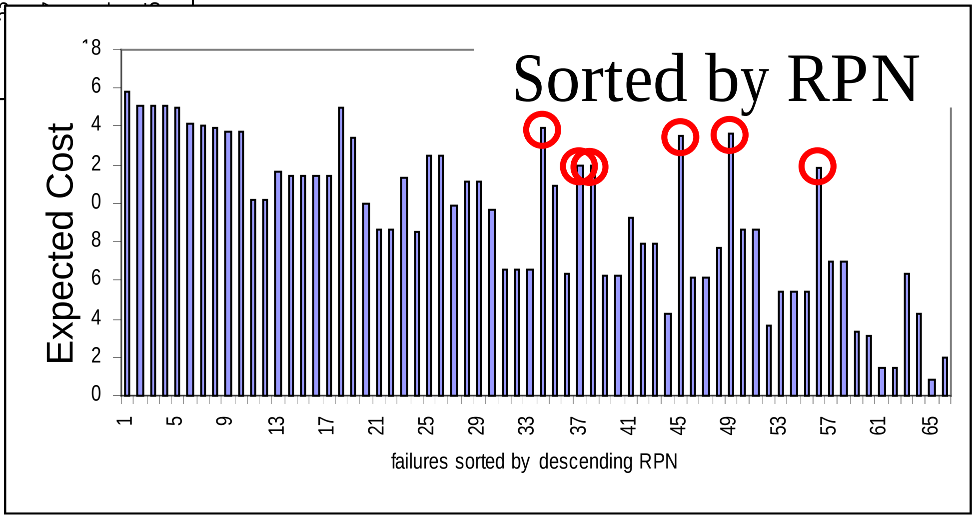


	Probability	Cost	Expected cost	Occurrence Rank, O	Severity Rank, S	RPN * (O x S x D)
a	0.75	\$50	\$ 37.50	10	1	10
b	6.66x10-5	\$500	\$ 0.033	3	10	30

RPN Priority Differs from Exp Cost



RPN can under-prioritize high risks



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)

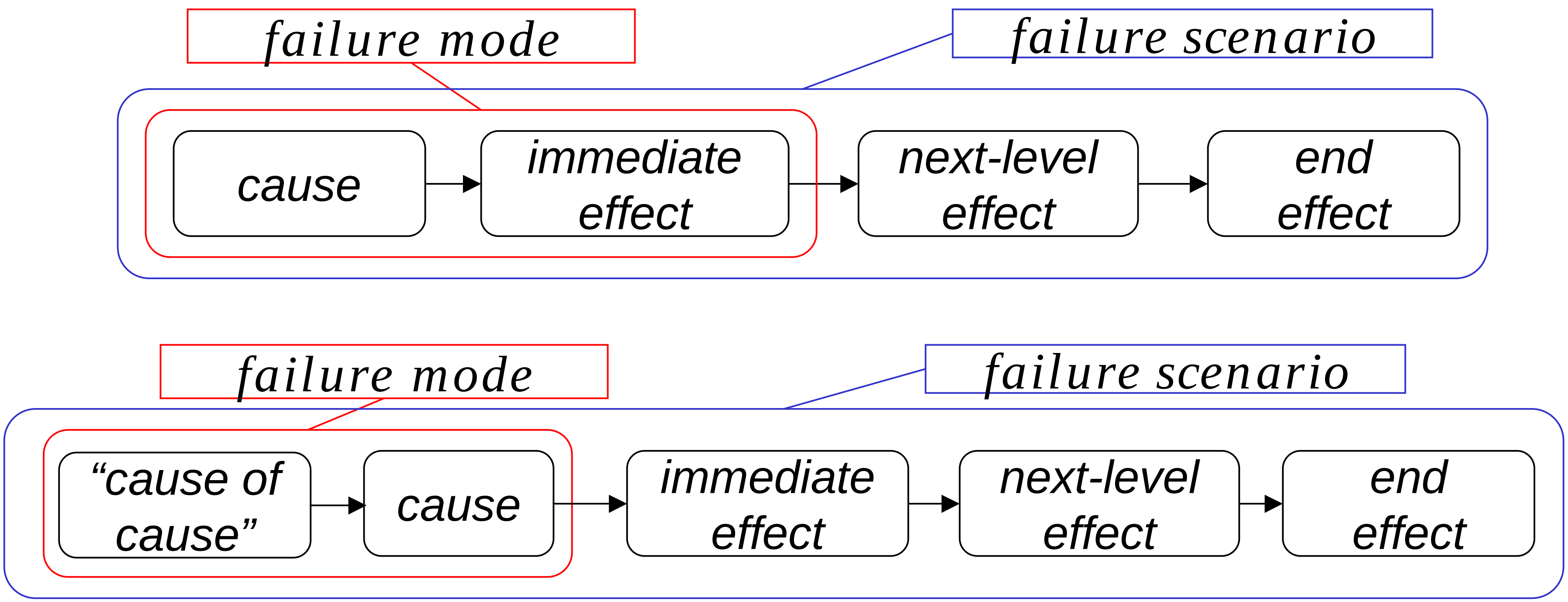
- Sometimes failure mode is a cause, sometimes an effect

  … → *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

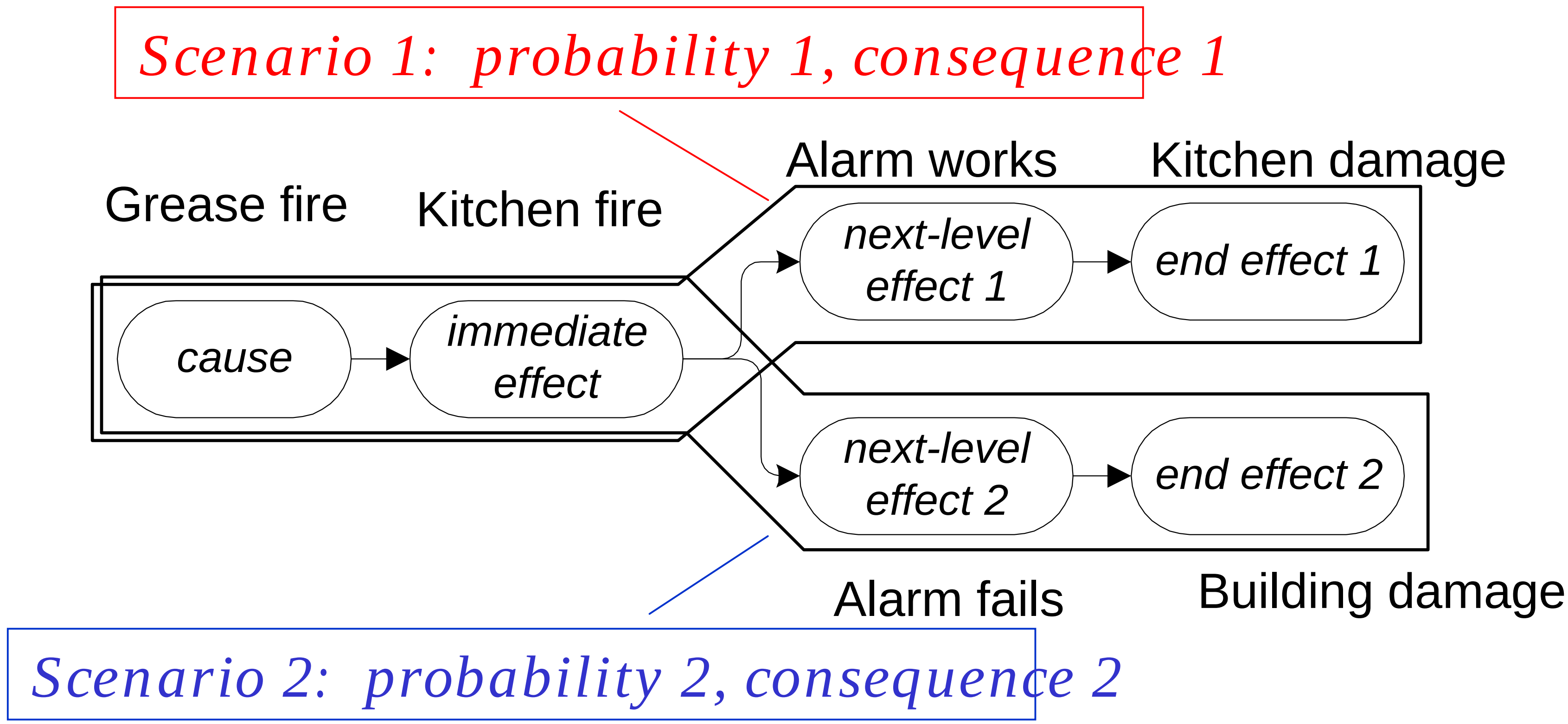
Failure Scenarios

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



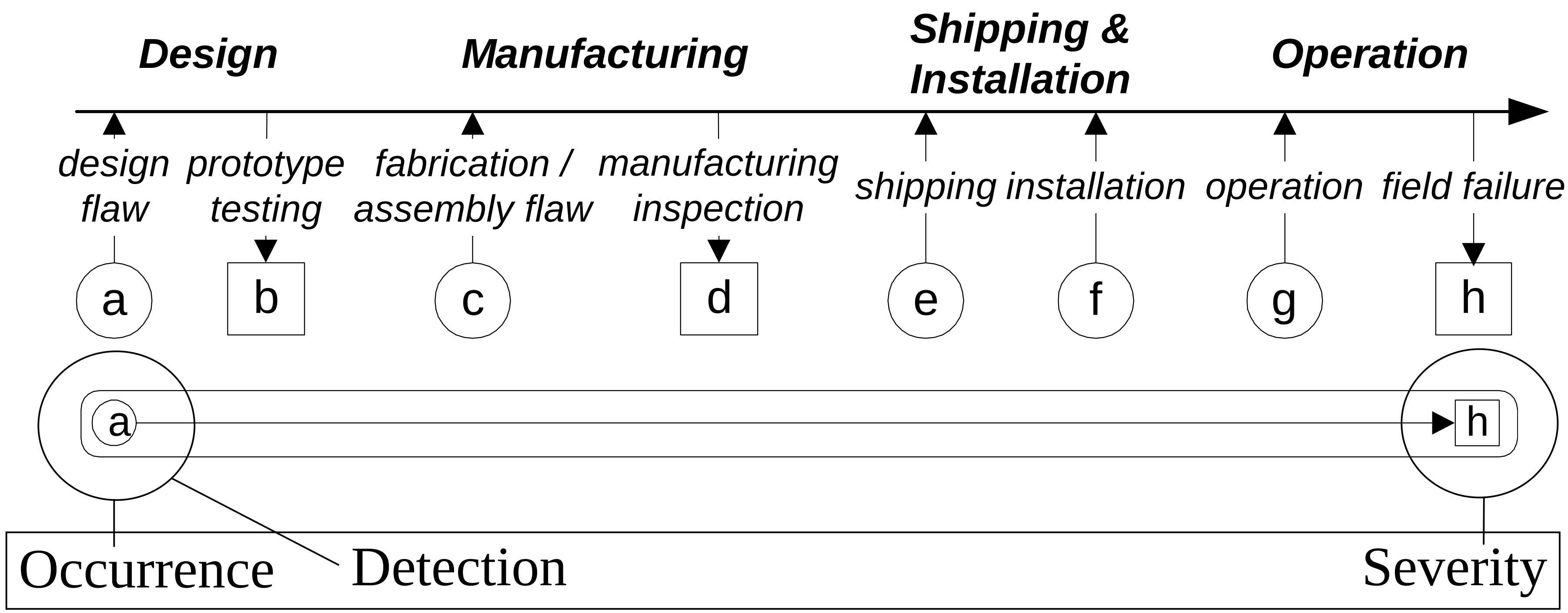
Failure Scenarios

- Scenarios have different probabilities and consequences

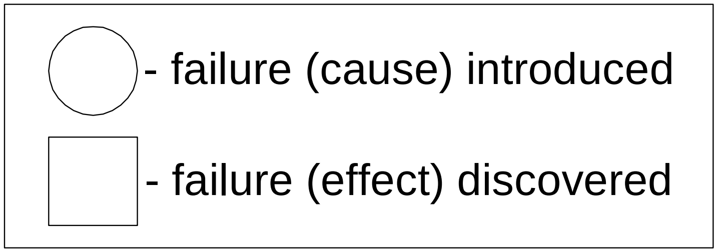


Conventional FMEA might list as one Failure Mode & one RPN Rating

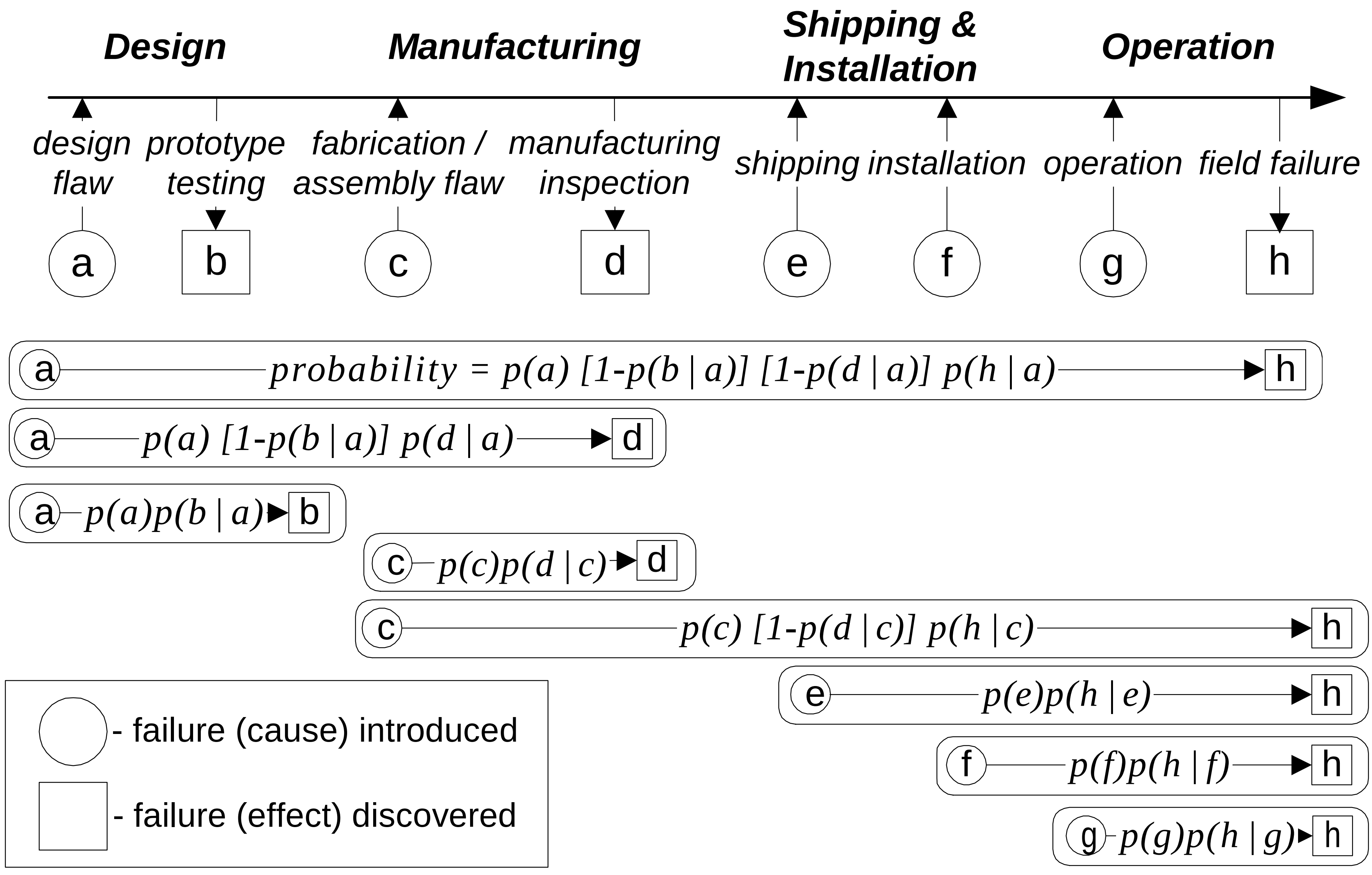
Traditional Failure "Modes"



RPN = O x S x D

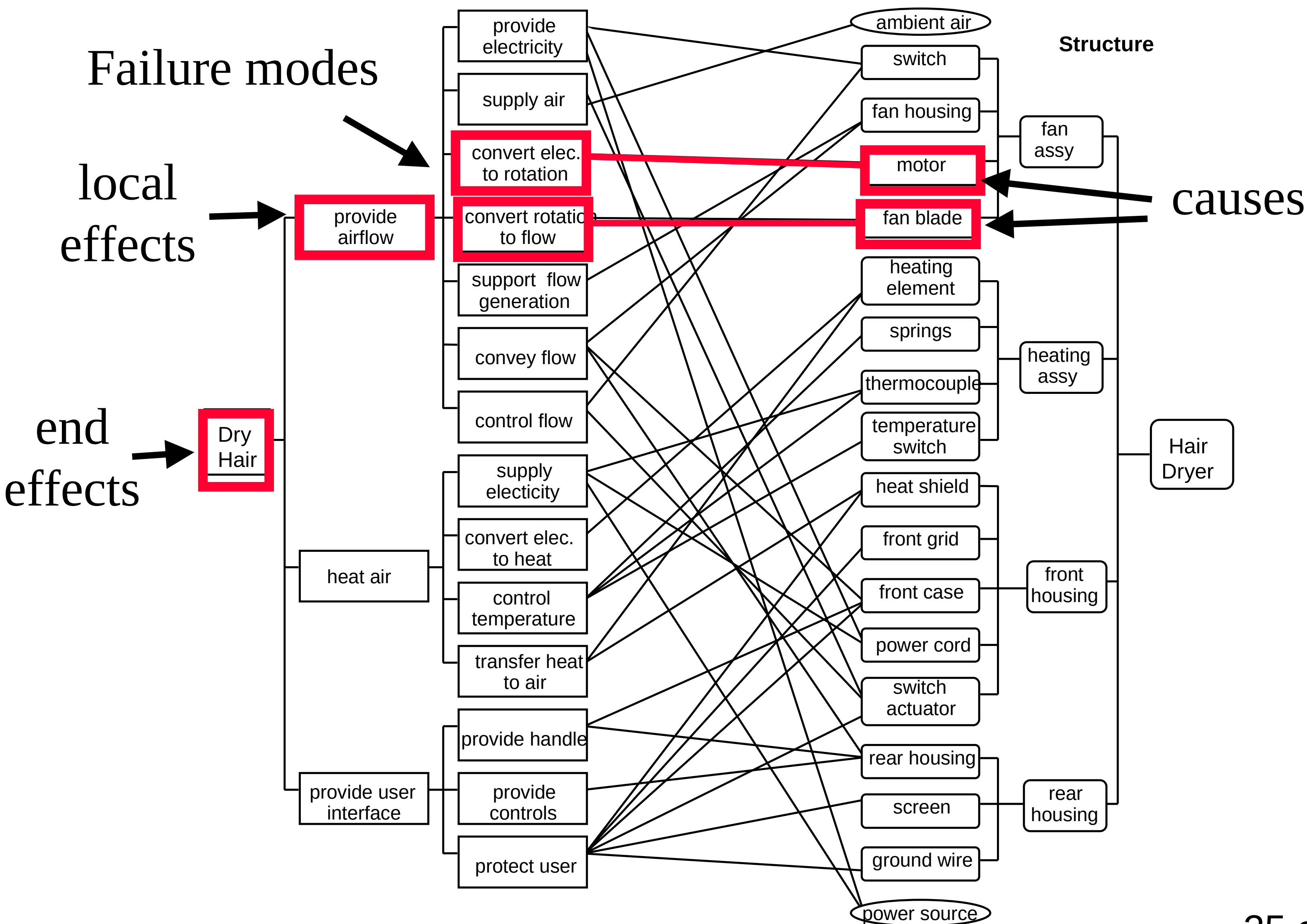


Life Cycle Failure Scenarios



Generating Failure Scenarios

Function-Structure Map for Hair Dryer

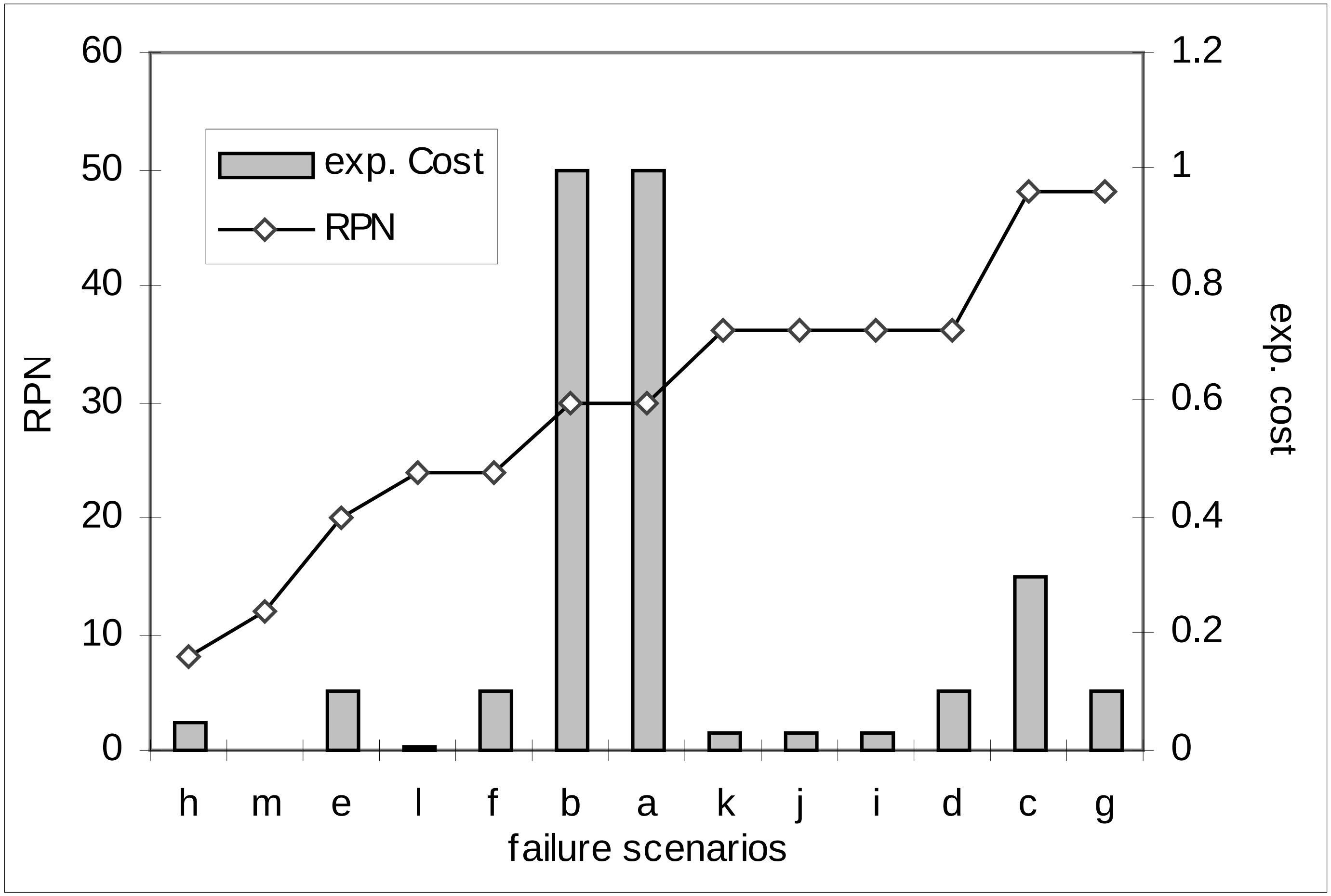


Example: Hair Dryer FMEA

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

- 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

Probability	from	to
VL	0	10e-5
L	10e-5	0.001
M	0.001	0.01
H	0.01	0.1
VH	0.1	1

Cost	from	to
VL	0	50
L	50	500
M	500	5,000
H	5,000	50,000
VH	>50,000	-

Example:

Prob. = Low
Cost = Medium

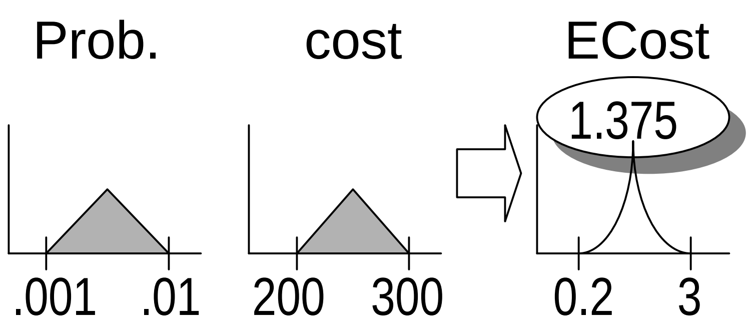
$$= \left(\frac{10e\text{-}5 + 0.001}{2}\right) \times \left(\frac{\$500 + \$5000}{2}\right)$$

$$= \$1.39$$

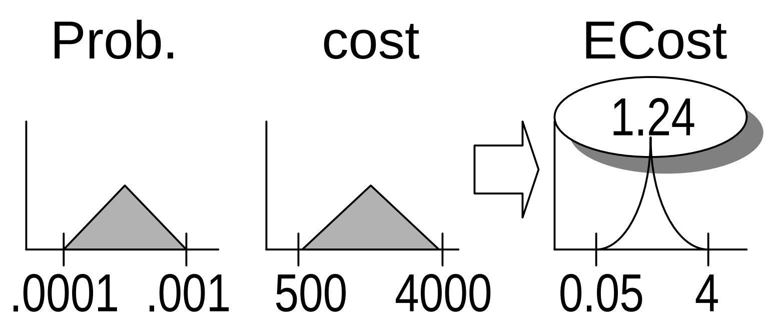
Once tables & ranges are defined, one can use:
(estimated probability) × (estimated cost)

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



Failure Scenario A



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 df*M* curriculum (me217.stanford.edu)
- On-going research project: Design & costing of next linear collider (Stanford/SLAC project)

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Questions??