Robustness Thinking
In Design for Reliability

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Matthew Hu’s Bio

1996 – Certified Robust Engineering Expert

2001 – ASQ SS CSSBB Exam Committee

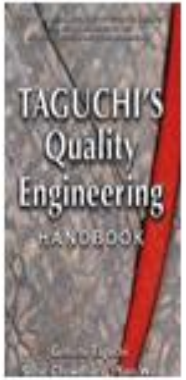
2002 – Creative Approach Award

2003 – Ford Customer Satisfaction Gold Winner Award

2004 – CAQ SS Promotion Council

2004

Robust Engineering Symposium
Enhancing Robust Design and DFSS With Aid of TRIZ & Axiomatic Design
The Most Creative Approach Award
Presented by Dr. G. Taguchi, ASI
October 14-16, 2002



Outline

- Introduction to DFR
- System Engineering process flow (V-Model)
- Variation
- Robustness Thinking in DfR Process
- Alignment to existing Product Development Process
- Factor DfR tasks into product development process
- Basic reliability tools for common reliability tasks linkage

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Introduction to DFR

What to do early in the development process (where changes are inexpensive) to design for reliability and prevent downstream problems in manufacturing and customer usage (where changes are very expensive)

- **Make design insensitive to uncontrollable user environment.**
- **Importance of “Front load uncontrollable user environment in product development process”.**

Reliability Story





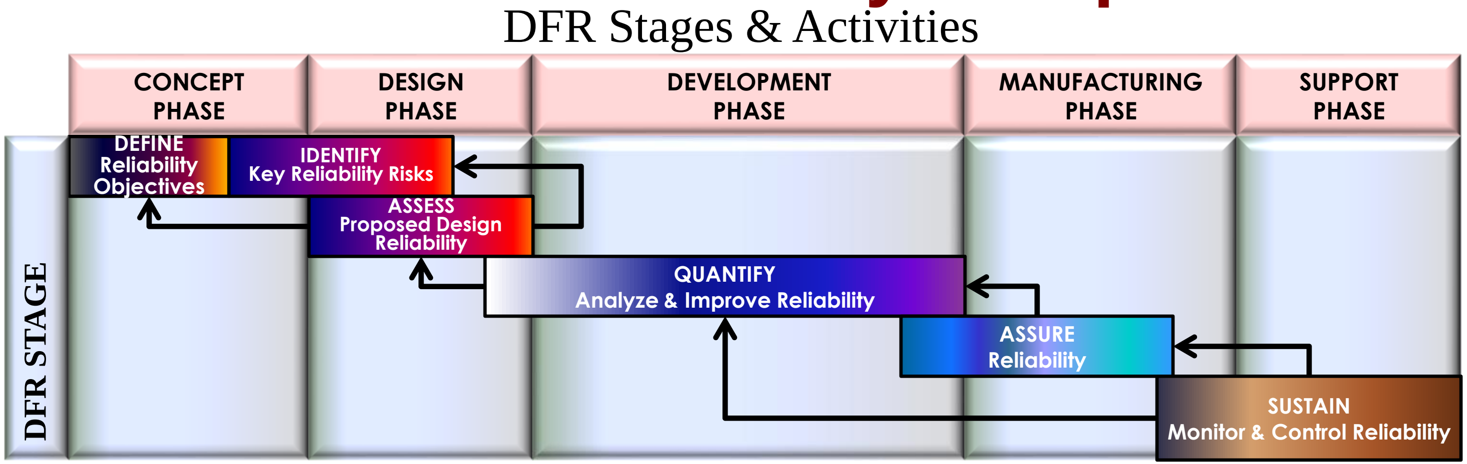
Reliability vs. Robustness

What is DfR (Design for Reliability)?

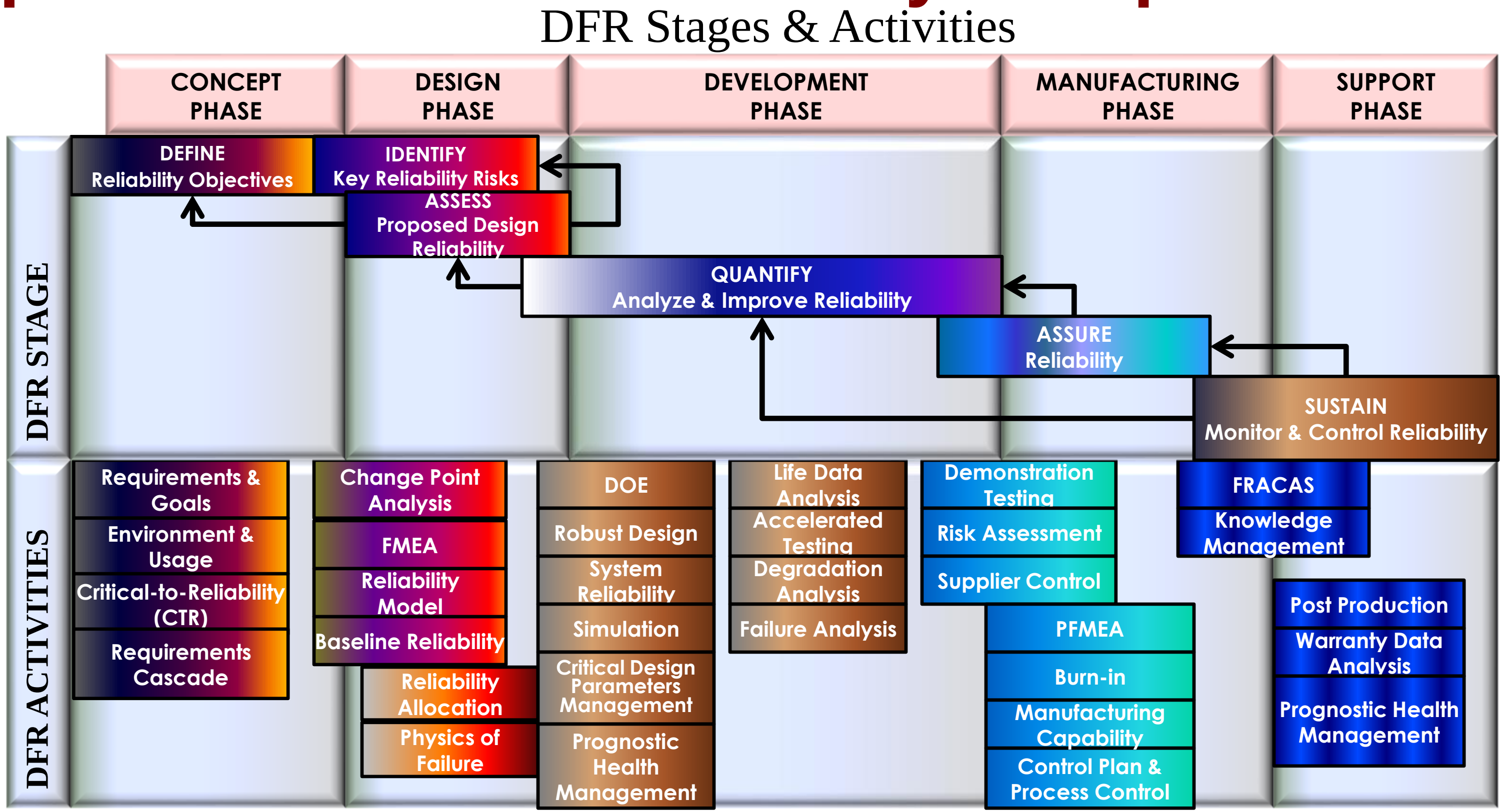
- A discipline that refers to the process of designing reliability into the products in order to:
  - Ensure customer expectation for reliability are fully met
  - Minimize overall costs and increase profit margins

- In simple terms…..whereas reliability analysis methods enable us to compute the reliability of a product, DfR provides us the PROCESS of assuring that the optimum/desired reliability is designed into the product

Typical DfR Process Used by Companies



Typical DfR Process Used by Companies



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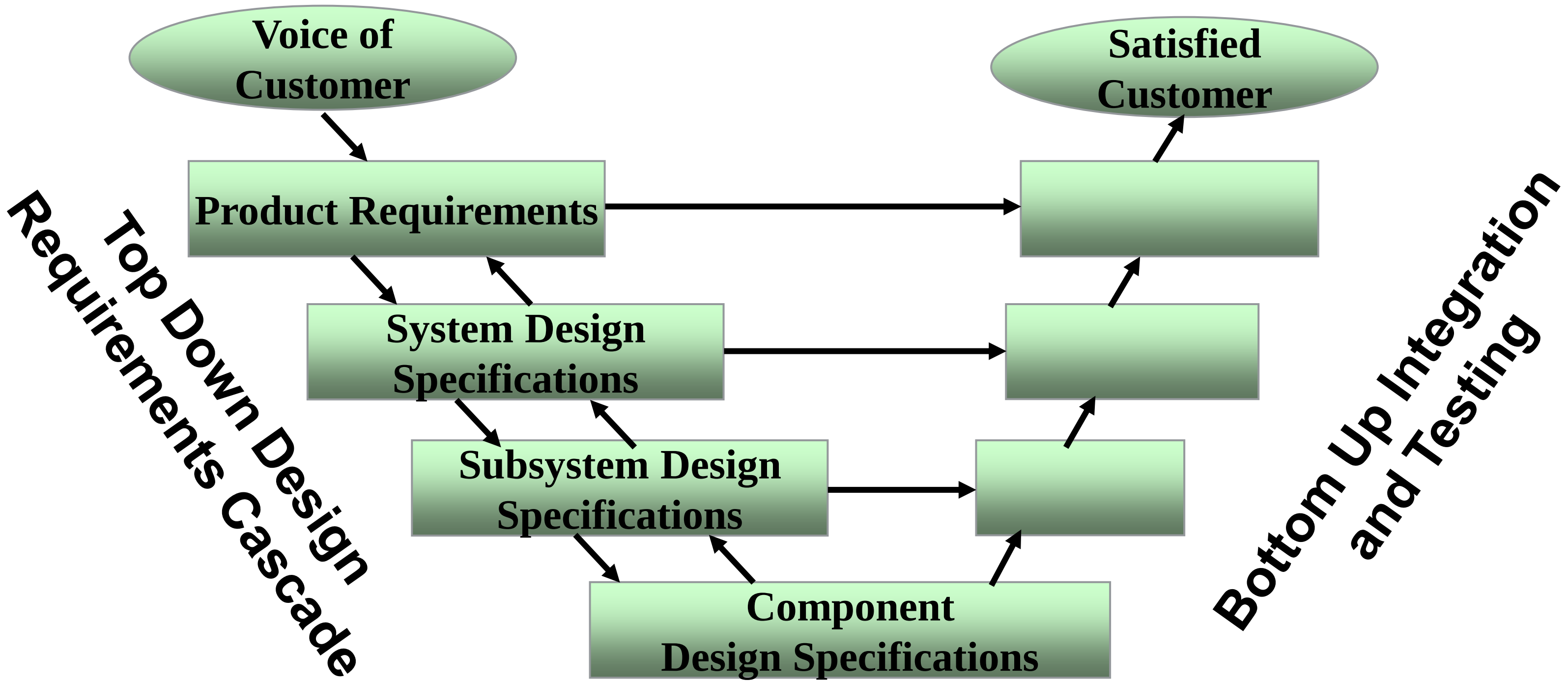
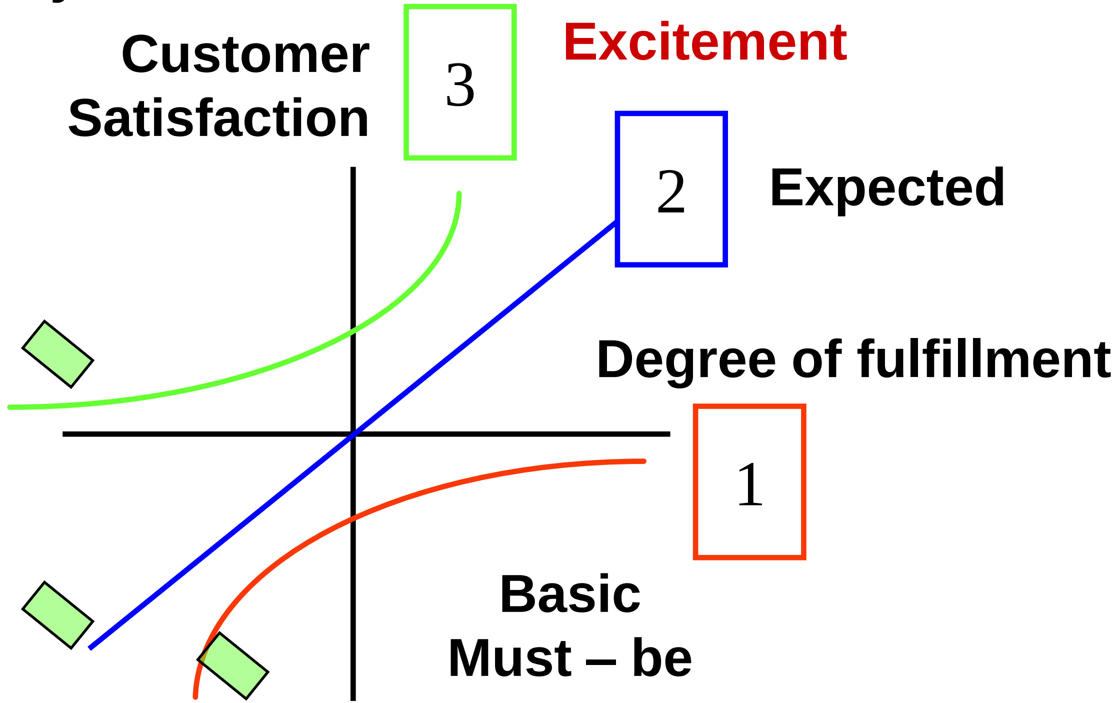
System Engineering (V-Model)

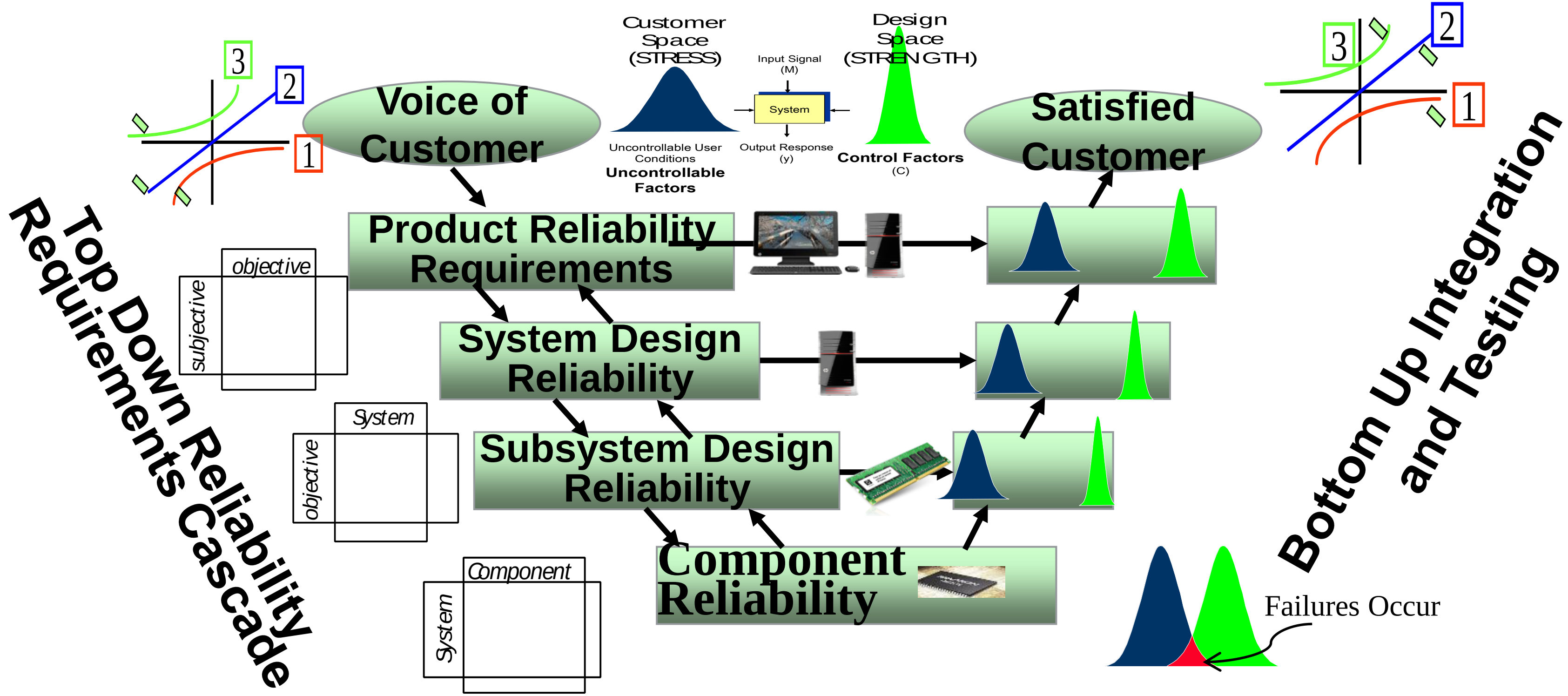


Reliability and Safety

Basic Quality: Must – be



Reliability Requirements Cascade



Begin With the End in Mind

(Covey - 7 Habits of Highly Effective People)

- **Will your customer always use your product under best conditions?**
- **Will your product always be manufactured under best conditions?**

No !

Variation Happens!!

Reliability in a World Full of Variation

Without Variation

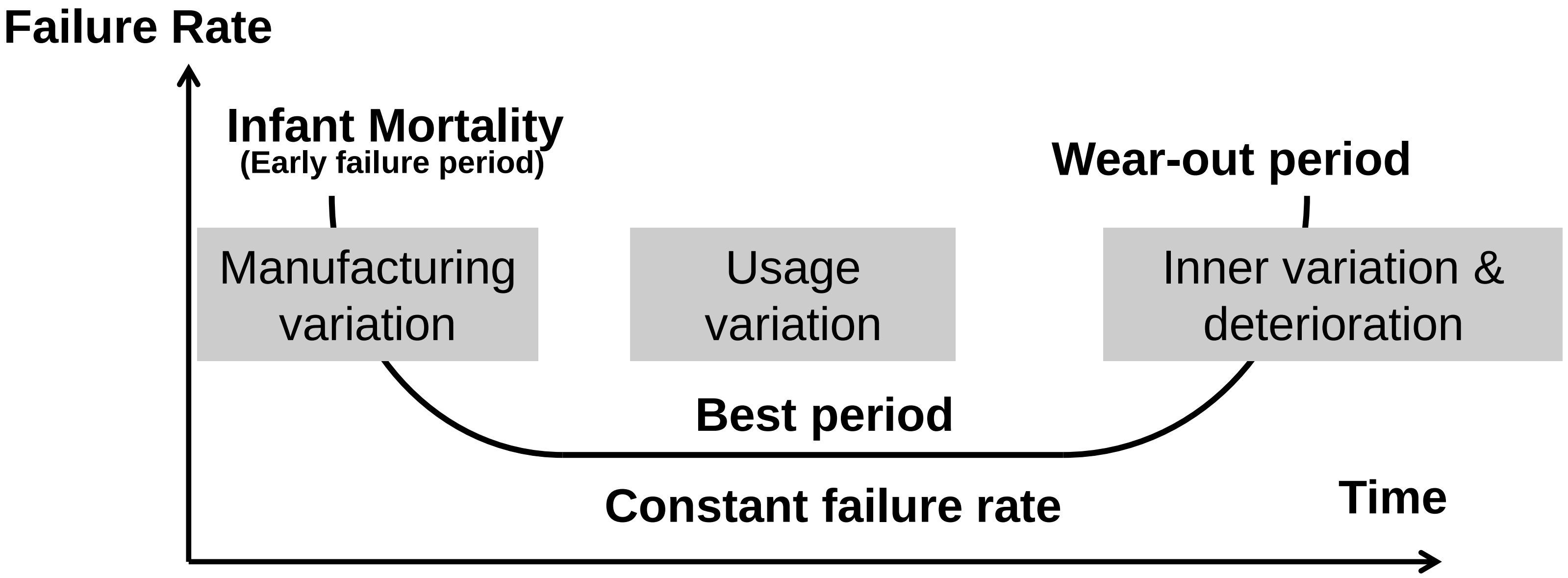
No World!

Life is Variation!

Variation Creates Problems:

- Deviations
- Disturbances
- Noise

Un-Reliability



Production Processes
Under Statistical Control?

Not Usually!!

Usage Environment
Under Statistical Control?

Control Methods and Tools In Bathtub Curve

Infant Mortality

Controls

- Selection of Low Defect rate Parts, Joints, Interconnects, etc.
- Selection of Low Defect Rate Processes
- Designing Process Capability

Conformance

Tools

- Robust Design/DOE
- Critical Parameter Management
- DFMEA/PFMEA/DFA/DFM
- Statistical Tolerancing
- Process Capability (Cp, Cpk)
- Mistake-Proofing, SPC, Control Plans
- HALT and HASS

Useful Life

Design Controls

- Selecting high reliability Parts, Joints, Interconnects, etc.
- Designing with the minimum number of Processes, Parts, Designing with low stress levels on Parts, Joints, Interconnects, etc.

Tools

- DFA – Part count reduction
- Reliability Data and Statistical Models
- Physics of Failures – Failure Mechanisms
- Robust Design/DOE/Prediction
- Test to Failure/HALT/ALT

Wear Out Life

Controls

- Selecting appropriate internal stress levels and materials to meet expected time to failure or replacement
- …..

Tools

- Reliability Data and Statistical Models
- Physics of Failures – Failure Mechanisms
- Robust Design/DOE
- Test to Failure/ALT

The Challenge of Reliability Theory Assumptions

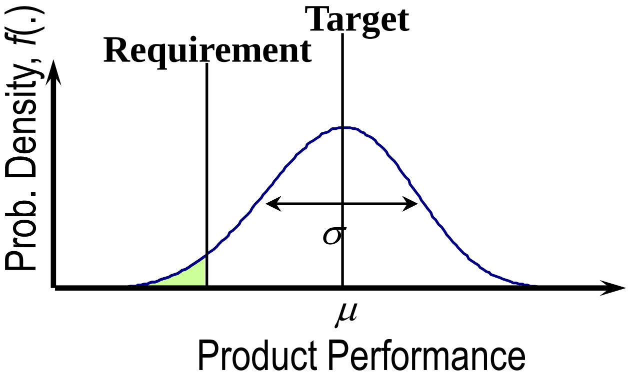
Probability models under the assumption:

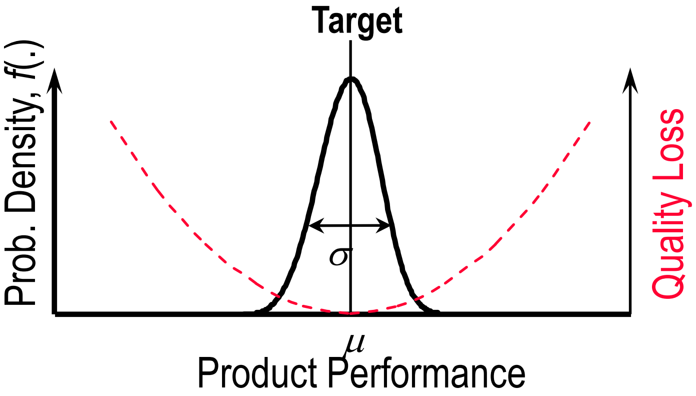
- **Processes under statistical control?**
  - Probably not!!!
- **Lagging indictors of reliability performance**
  - The design is created before testing
  - Usage feedback is even much later

Back to Basics

- **Work with the failure mechanisms**
- **And their relations to Variation!**

Reliability and Robustness (An Engineering Measure of Reliability)





Reliability: *probability* of a product performing its intended function for a specified life under the operating conditions encountered.

Q: How do you know the f(.) when a design is new?

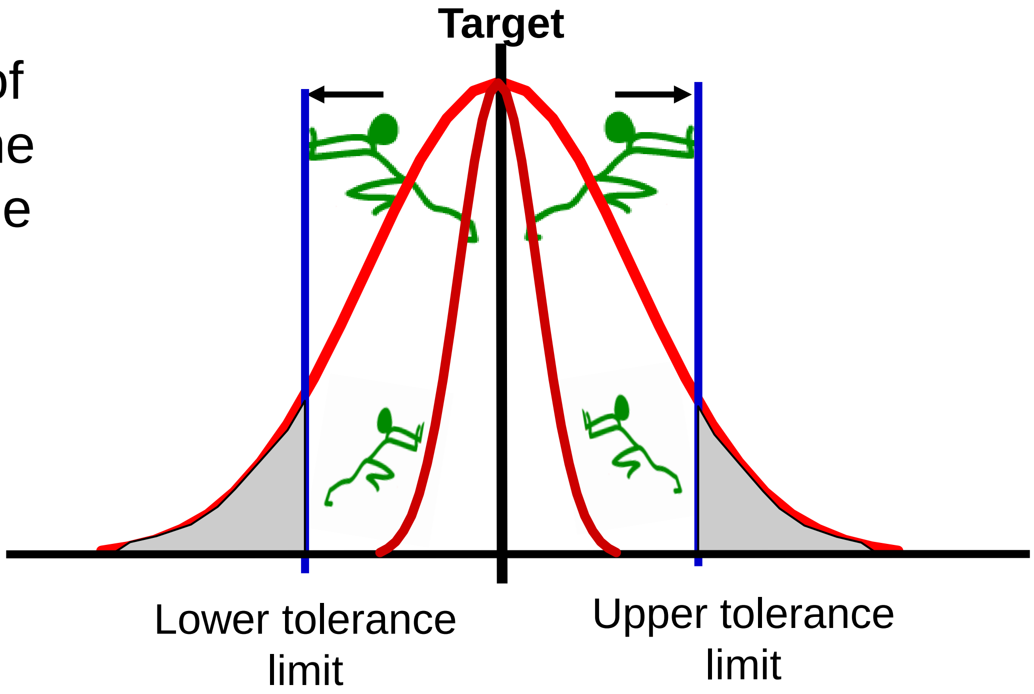
*Computing probability of success requires knowledge of m, s, **f (.)***

Robustness: ability of a product to perform its intended function consistently in the presence of uncontrollable user environment (noise) during its intended life. In other words, the product is insensitive to

Assessing robustness requires knowledge of m, s

Robustness Solves the Problem

- Robustness - low variation of ideal performance around the target value *IN SPITE OF* the effects of Noise Factors (uncontrollable user environment)



Deterministic Design

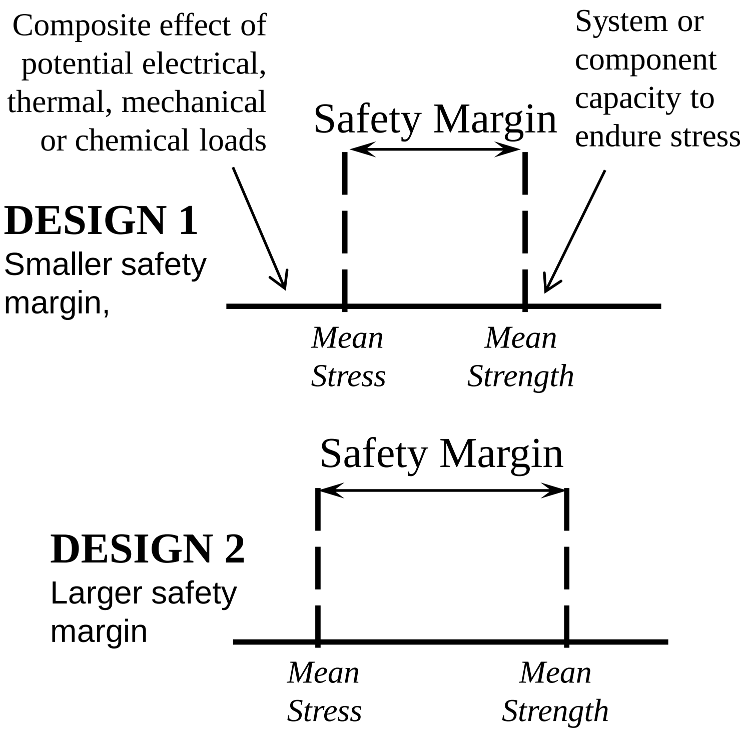
Under a simple stress-strength framework, design nominal are chosen to provide “strength” that exceeds the “stress” the product will experience

It is known that stresses and strengths may vary, so safety margins are selected to minimize risk of failure, based on

- Rules of Thumb
- Past Experience

Without some probabilistic analysis, understanding of the nature of the variability and how it combines to affect performance is limited

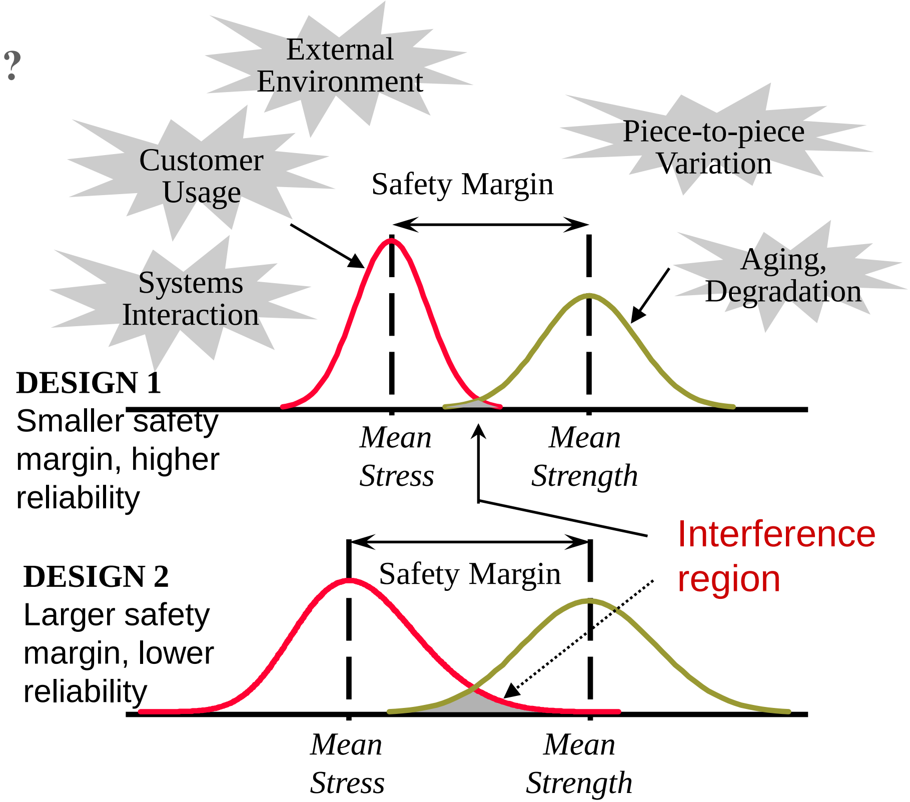
Consider two designs from a solely deterministic perspective. Which is less likely to fail?



Probabilistic Design

How can design be insensitive to noise…?

- Probabilistic analysis helps one understand the shape and dispersion of variability caused by noise
- The interference region between stress and strength defines the probability of failure--this determines reliability
- A design with a larger safety factor may have lower reliability depending upon stress and strength variability



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Robustness and Efficiency in Product Development

Why Robust Design?

- The answer to this question can be summed in one word, …EFFICIENCY.
- Robust Design enables the engineer to efficiently gather the technological information required to produce high quality/Reliability, low cost products through preventative means.
- It is more efficient to prevent problems using robustness optimization than to fix problems encountered in later stages of development.
- Robustness to important (major) Noise Factors during upstream development will be repeatable downstream under actual conditions of mfg. and use.

What is Robustness?

Webster's dictionary defines robustness as:

- being powerfully built, sturdy
- boisterous, rough
- marked by richness and fullness

Dr. Taguchi defines robustness as:

- the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user's environment) at the lowest cost.

Robust Design

Make design insensitive to the uncontrollable user environment (noise)

- **Concentrates on:**
  - identifying the "ideal function(s)" for a specific technology or product/process based on its energy transformation, then selectively choosing the best levels of design parameters that optimize performance reliably (even in the presence of factors causing variability) at lowest cost.
  - application of two-step optimization.

Robustness – An Approach to Make Money

- Robustness reduces performance variations and achieves Six Sigma quality
- Avoids failure modes
- Achieves customer satisfaction
- Also shortens development time to market – reduces build/test/fix

What Are the Source of Variation?

The 5 types of Noise factors that disturb ideal function

		Noise Factor	Caused by
Inner Noise (Capacity)	**1**	Piece-to-piece variation of part properties (such as dimensions)	Production rate
	2	Changes over time in dimensions or strength (such as wear out, fatigue, deterioration, chemical degradation)	Exposure to repetitive demand
Outer Noise (Demand)	**3**	Customer usage and duty cycle	Conditions of use
	4	External operating environment	Climatic and application conditions
	5	Internal operating environment (error states from one component being received as a noise factor by another)	Component & system interactions

Noise Impact in Bathtub-Curve

Strength Noises

1. Piece to piece/comp.-comp. variation

2. Aging/Wear out/ strength over time / cycles

Stress Noise

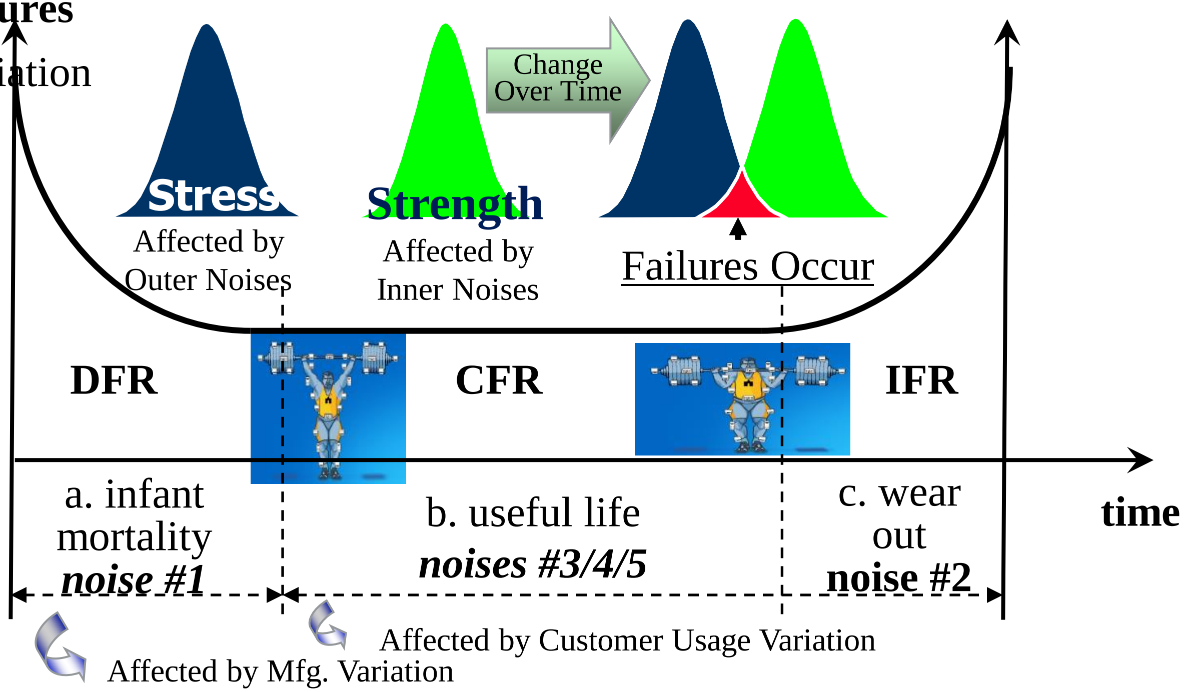
Conditions of Use

3. Customers usage and duty cycle or usage profile

Operating environment

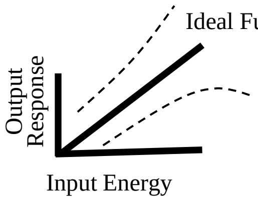
4. External (climate/location)

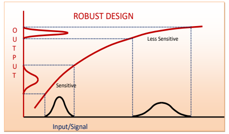
5. Internal subsystems /components interactions / interfaces



DFR=decrease failure rate, CFR=constant failure rate, IFR=increase failure rate

Robust Design for Reliability





Minimize Sensitivity to Noise
- Concept / System Design
- Robust Parameter Design

Reduce Rate of change of product parameters
-Tolerance Design

Robust Design for Reliability

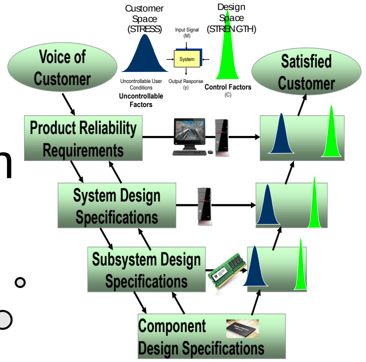
Redundancy
(Cost of failures vs. cost of providing redundant components

Capable **Manufacturing** Process

Robust Engineering

Robust Engineering Emphasizes CI* on Three Main Design Stages

- System Design
- Parameter Design
- Tolerance Design



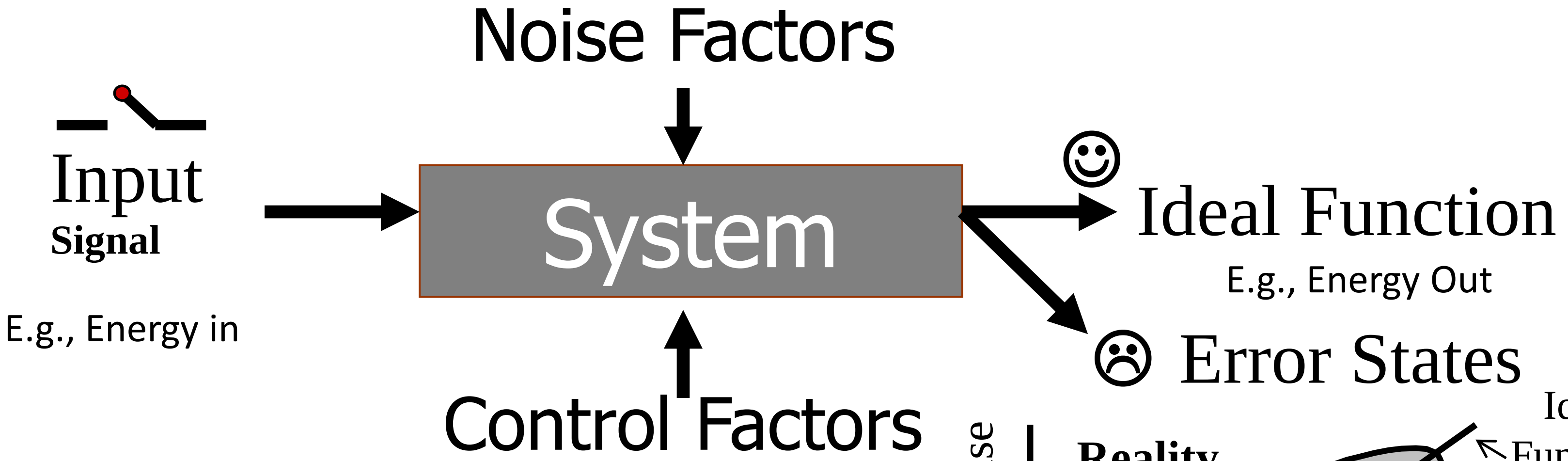
Upfront Critical Thinking and Discipline

Robust Design Principles

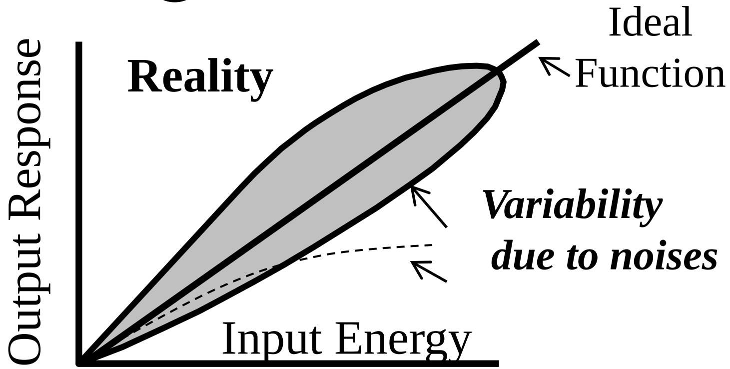
1. Identify and Select Proper System Output Response (s)
2. Measure Functions using S/N** Ratio or Equivalent
3. Take Advantage of Interactions between Control & Noise Factors
4. Use Orthogonal Arrays
5. Apply Two-step Optimization

Note: *CI: Continuous Improvement, S/N=Signal-to-Ratio

Model for Robustness Thinking



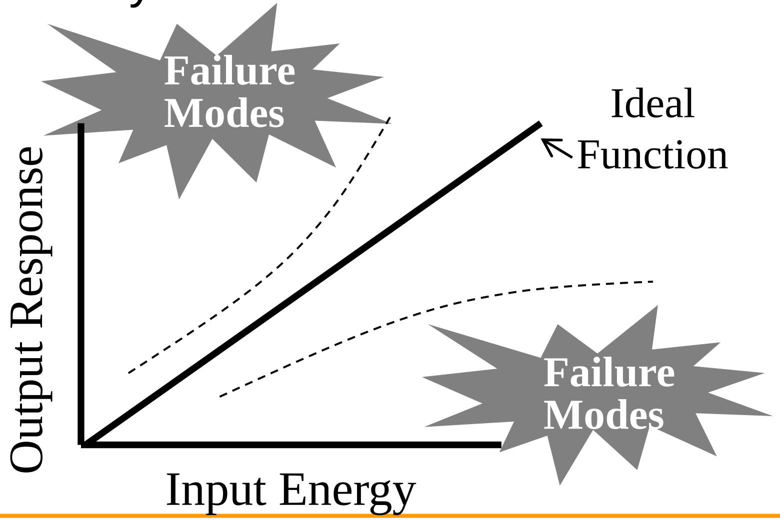
Ideally 100% of input energy (the signal) should convert into 100% ideal function.



Ideal Response and Failure Mode Avoidance

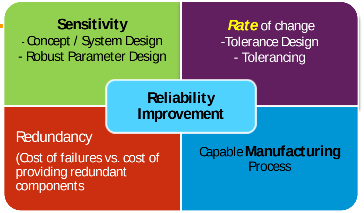
- Want Ideal Response to Signal – usually straight-line function
- Actual response is determined by values of control factors and noise factors
- If noise factors are suppressed early, then difficult problems only appear late
- Introduce noise early!

- Reliability data
- Warranty information
- Cp/Cpk
- Scrap & Rework
- Failure Rate
- % defective
- Etc.



S/N ratio (Larger-the-Better)
An Engineering Measure of Reliability

High Level Measures of a Design Concept



- **Bad Concepts cannot be recouped by “brilliant Detailed Design”**

Bad Concepts

- Cannot be optimized
- Will create persistent problems in manufacturing and reliability
- Cannot be corrected by Detailed Design

High Warranty Cost

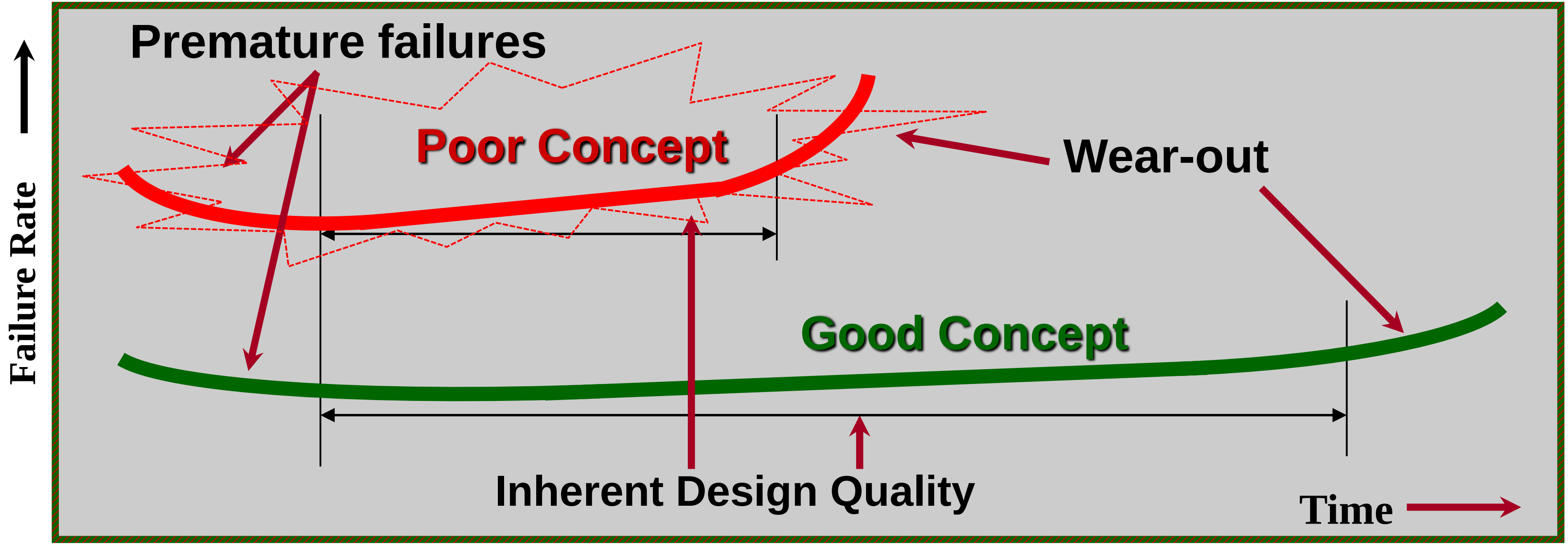
Good Concepts

- Can be optimized
- Do not require expensive tolerance control in manufacturing
- Are Robust under real world usage conditions

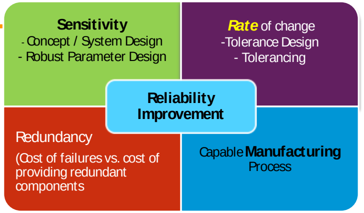
Low Warranty Cost

High Level Measures of a Design Concept

- Good Concepts can be optimized to provide superior Reliability.
- Poor Concepts cannot.



Quality and Reliability

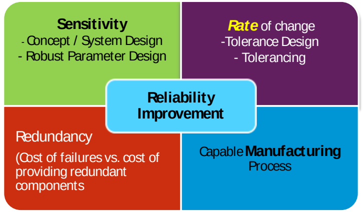


"In fact, you can have quality without reliability and you can have reliability without quality."

"You buy based on quality.
You come back and buy again based on reliability."

*H. James Harrington and Leslie C. Anderson, *Reliability Simplified: Going Beyond Quality to Keep Customers for Life*, McGraw-Hill, New York, 1999, p. 3.

Concept Design is Key to Reliability

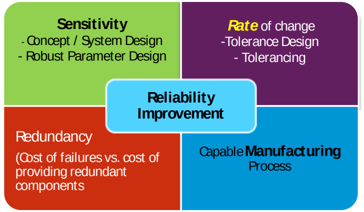


Good Concept Designs **can be Optimized** to yield high Reliability.

Poor Concept Designs **cannot be Optimized** to yield high Reliability.

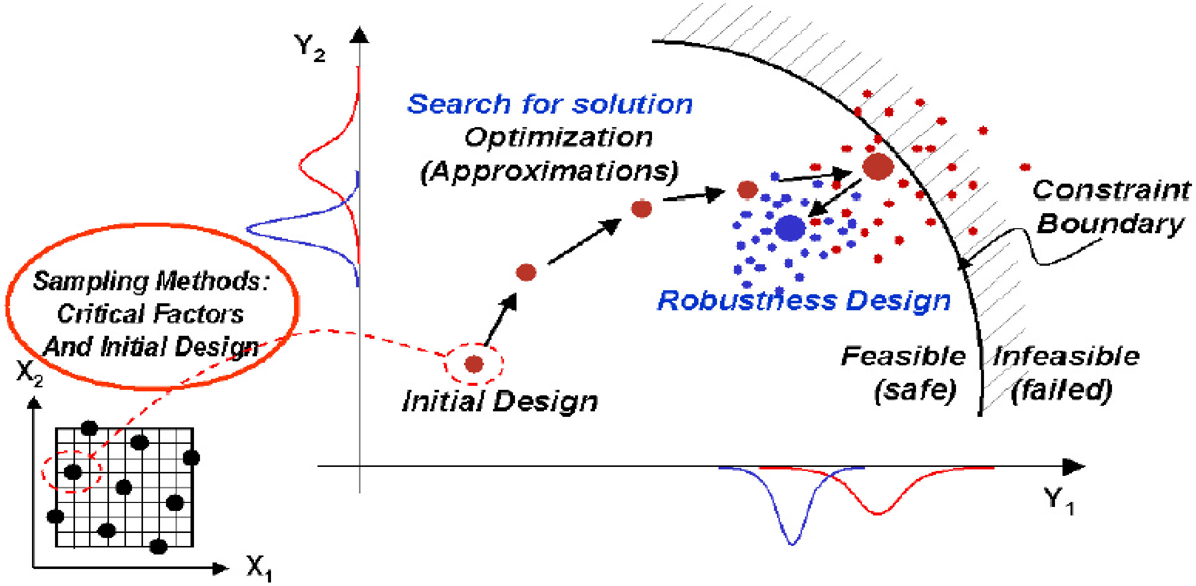
How do you know the limitation of a given concept design?

System Thinking & Robustness

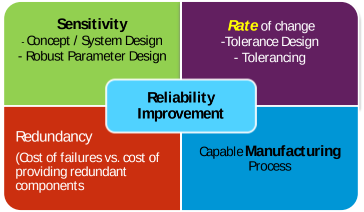


The achievement of higher reliability can also be viewed as an improvement to Robustness.

Design Space Optimal Points Searching

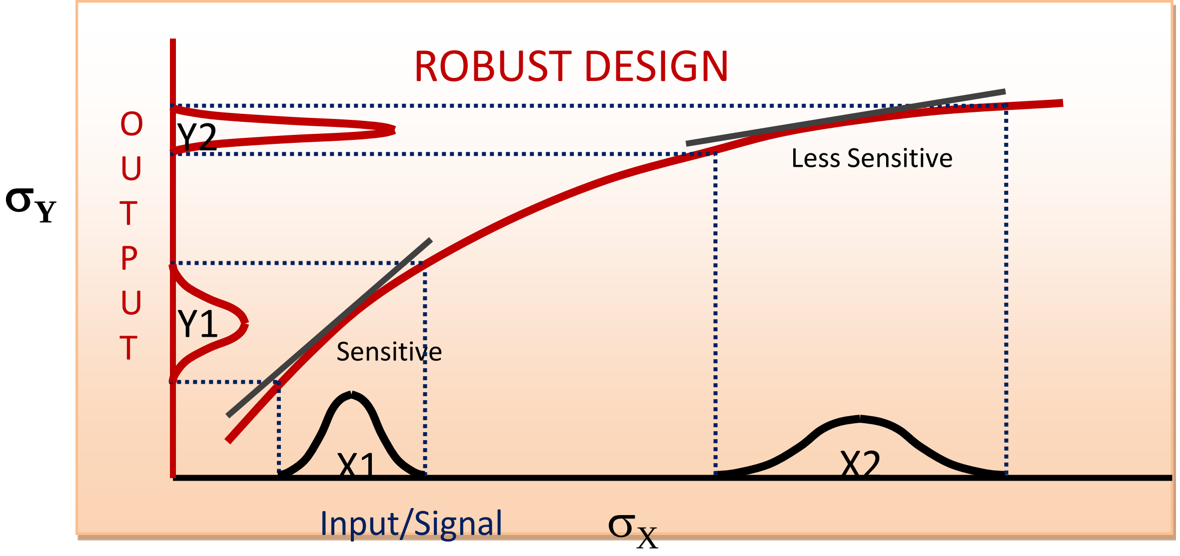


Create Robust Design



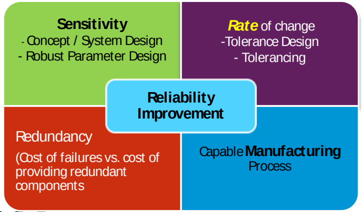
The principle of parameter design is a powerful methodology to increase the distance from the failure mode.

Exploiting Non-Linearity



X2 results in less variation in Y

Results of Robust Design Effort (Shrink and Shift)



- Reduced variation
- Improved targeted performance
- Improved reliability
- Improved customer satisfaction

Step 2

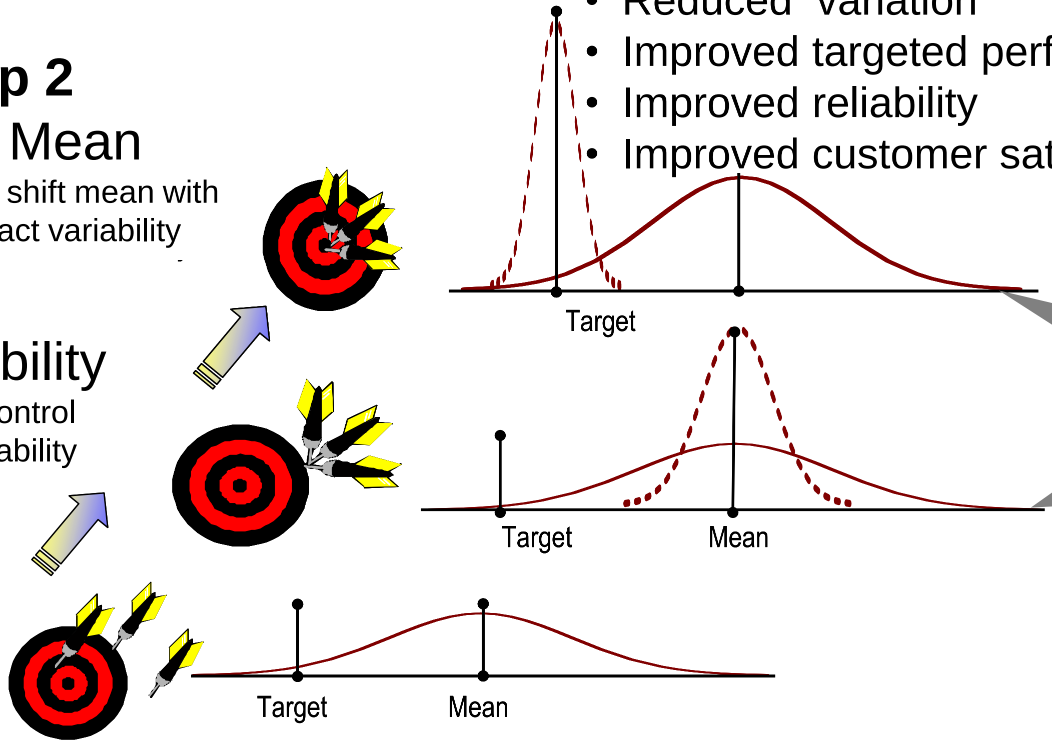
Adjust Mean

Select factors to shift mean with minimum impact variability

Step 1

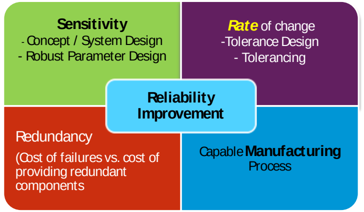
Reduce Variability

Take advantage of control factors affecting variability

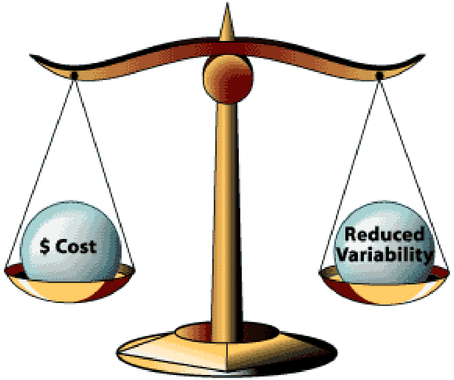


Assess the limitation of a given design

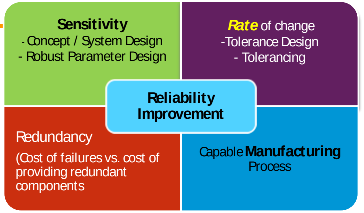
Tolerance Design – (1)



- **Specification**
  - Consists of nominal value and tolerances
- **Nominal value**
  - Ideal dimension or target value for meeting customer requirement
- **Tolerance**
  - Allowable variation above and/or below nominal value
  - Recognizes natural variation (common causes)



Tolerance Design – (2)



- Consider tradeoff between costs and performance
- Too tight tolerances = unnecessary cost
- Too loose tolerances = not meeting customer requirements
- End result: too loose or too tight is going to cost money!

Failure Mode Avoidance

Failure Mode Avoidance

- Lusser (in the 1950-ties)
  - Robert Lusser
- FMEA
  - Failure Mode and Effects analysis
  - Physics of Failure
- Clausing (Xerox/MIT)
  - Operating Window
- Pat O´Connor
- Taguchi
- Davis (Ford)
- Frame: DFSS e.g Park, Creveling et al. ….

Limitations of Current DfR

- Overreliance on MTBF calculations & standardized product testing
  - Provides no motivation for failure avoidance
- Incorporation of HALT and failure analysis (HALT is test, not DfR; failure analysis is too late)
- …

Reliability is Failure Mode Avoidance

A reliable product is one that is robust and mistake free.

Two Root Causes

Failure Type	Lack of robustness	Mistakes
Hard failures (product function ceases)	Deterioration	Primary
Soft failure (degraded performance)	Primary	Occasional

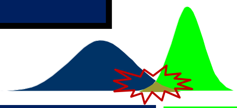
Noises (uncontrollable usage environment)

Stress (Demand)

- **3.Customer duty cycle**
- **4.External environment**
- **5.System interactions**

Strength (Capacity)

- **1.Production variations**
- **2.Changes over time/cycle**



stress (demand)

strength (capacity)

Vigilance

- Operational Definitions
- Minimize Deviations
- FMEA & Poka-Yoke
- Principles
- Warranty Prevention
- Re-usability
- Product Quality System
- Change Point Management

How To Avoid Failure Mode?

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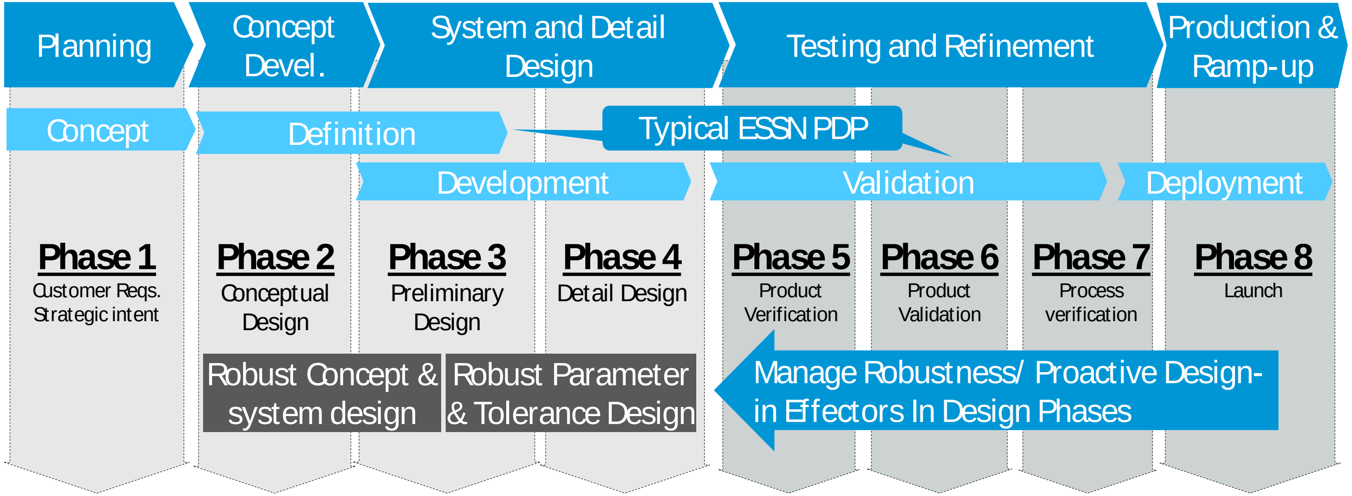
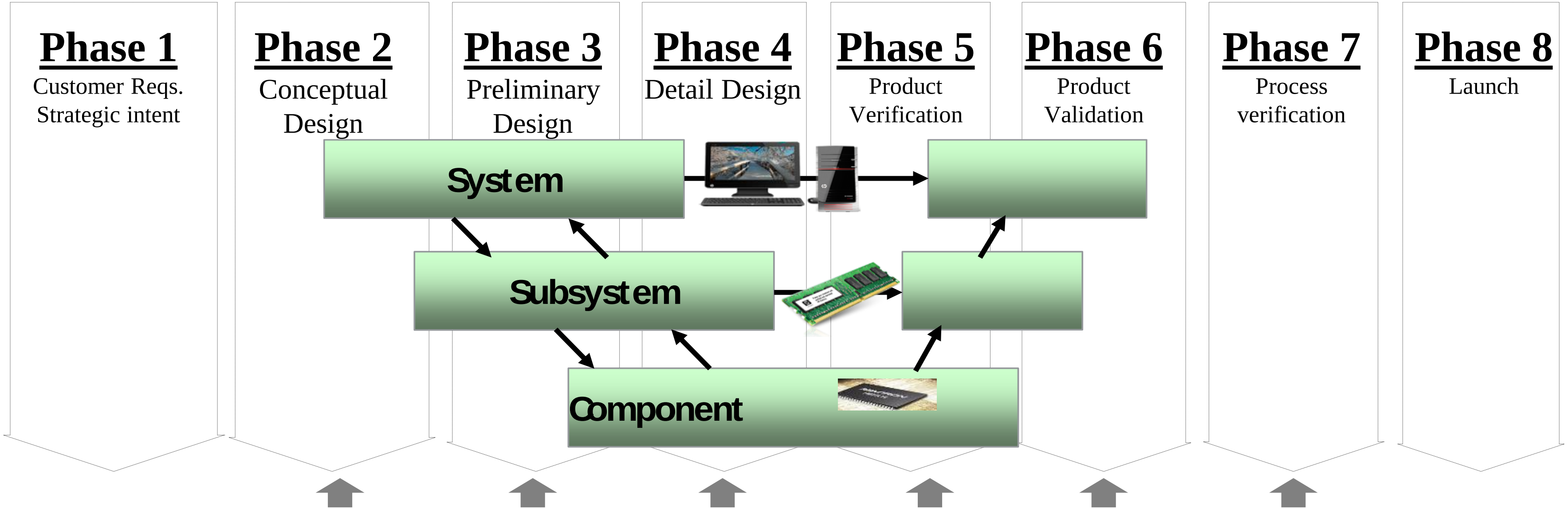
Cultural Change

- Develop robust technology and robust design
- Early introduction of noise goes against engineers' culture of making product look good
- Two most important elements for success:
  - – Early introduction of noise
  - – Recognition that performance variation must be reduced – while noise values are large



Robust Design for Reliability Timing

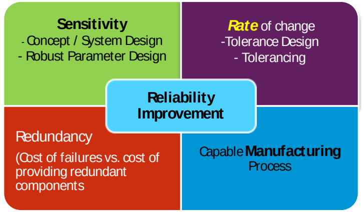


Robust Design on Technology Stream, New Product & Process Technologies

CONCEPTUAL ROBUSTNESS ASSESSMENT
SYSTEM (PRODUCT) PARAMETER DESIGN
TOLERANCE DESIGN

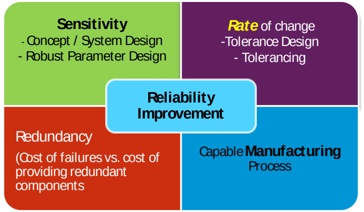
SYSTEM VERIFICATION TEST
PROCESS PARAMETER DESIGN
QC /SPC– ON LINE QUALITY CONTROL (FACTORY FLOOR)

Robustness "Rules of Engagement"



1. Concentrate on **Ideal Function**, and establish a way to measure it; do not use symptoms of poor quality
2. Identify sources of the **five types of noise** and expected magnitudes
3. Introduce product noise **early**. Drive the performance away from ideal situation
4. Concentrate on the *effects* of the noise, rather than the noise themselves
5. Understand how error states and noise factors cross system interfaces and boundaries
6. Develop a noise factor management strategy

Robustness "Rules of Engagement"



7. Work out how to include remaining Noise Factors in tests
8. Plan a robustness assessment of current design to compare against ideal performance.
9. Where robustness improvement strategy is obvious from knowledge of physics, DO IT!
10. Where robustness improvement is not obvious from current knowledge of the physics, plan parameter design studies (using DoE if necessary) to discover the improvement
11. Management needs to design this into the Product Design Process and check that it is done to an appropriate degree

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Robust Design Tasks in Product Development Process

Concept — Product Concept Development — **Definition** — Product Data Development — **Develop-ment** — Verification / Validation — **Validation** — Batch Production — **Deploy-ment**

Note: The highlighted in dark blue are the key events in Robust Engineering / DFSS

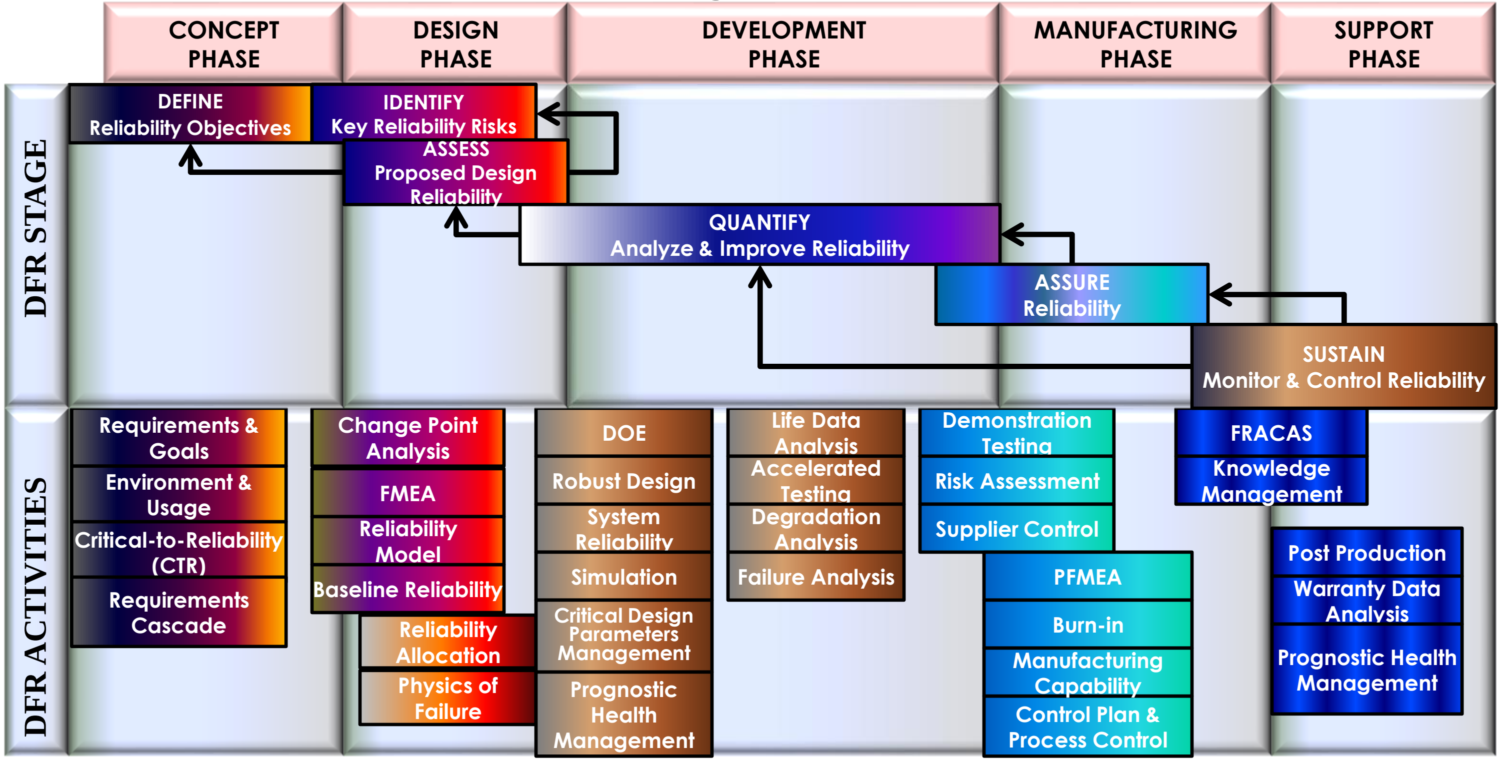
- Capture Customer Wants & Needs
- Feasibility Study / Assess Technology
- Validate Business Case
- Convert customer wants & needs to measurable CTS's Values
- Develop DfX Requirements
- Identify operational & internal noise (product variation)
- Identify/select high impact external noise (external environments)
- Assess/ Mitigate Risks of Potential Failures & Prevent Repeating Past Mistake
- Develop Reliability & Robustness Checklist
- Develop Noise Management Strategies
- Develop Reliability & Robustness Demonstration Plan
- Assess Concept Robustness
- Conduct Analytical Reliability & Robustness Studies
- Develop Transfer Functions
- Optimize Design Parameters & Values
- Optimize tolerances
- Demonstrate Reliability& Robustness
- Apply Noise Strategy
- Predict Design Capability & Manage Critical Parameters
- Update Transfer Function
- Flow down & uncouple /decouple function requirements
- Develop Manufacturing Process Capability & Control Plan
- Plan Test for Functional/Prototypes/Verification
- Conduct test for Functional Prototypes/ Verification
- Verify Process & Measurement Capabilities
- Implement and institutionalize Design, Measurement & Process Control
- Leverage to Other Applications

- Note this proactive design quality process is highly iterative
- The tasks basically follows this process flow but tasks need not be sequential
- The detail approach of each task may vary with each iteration loop

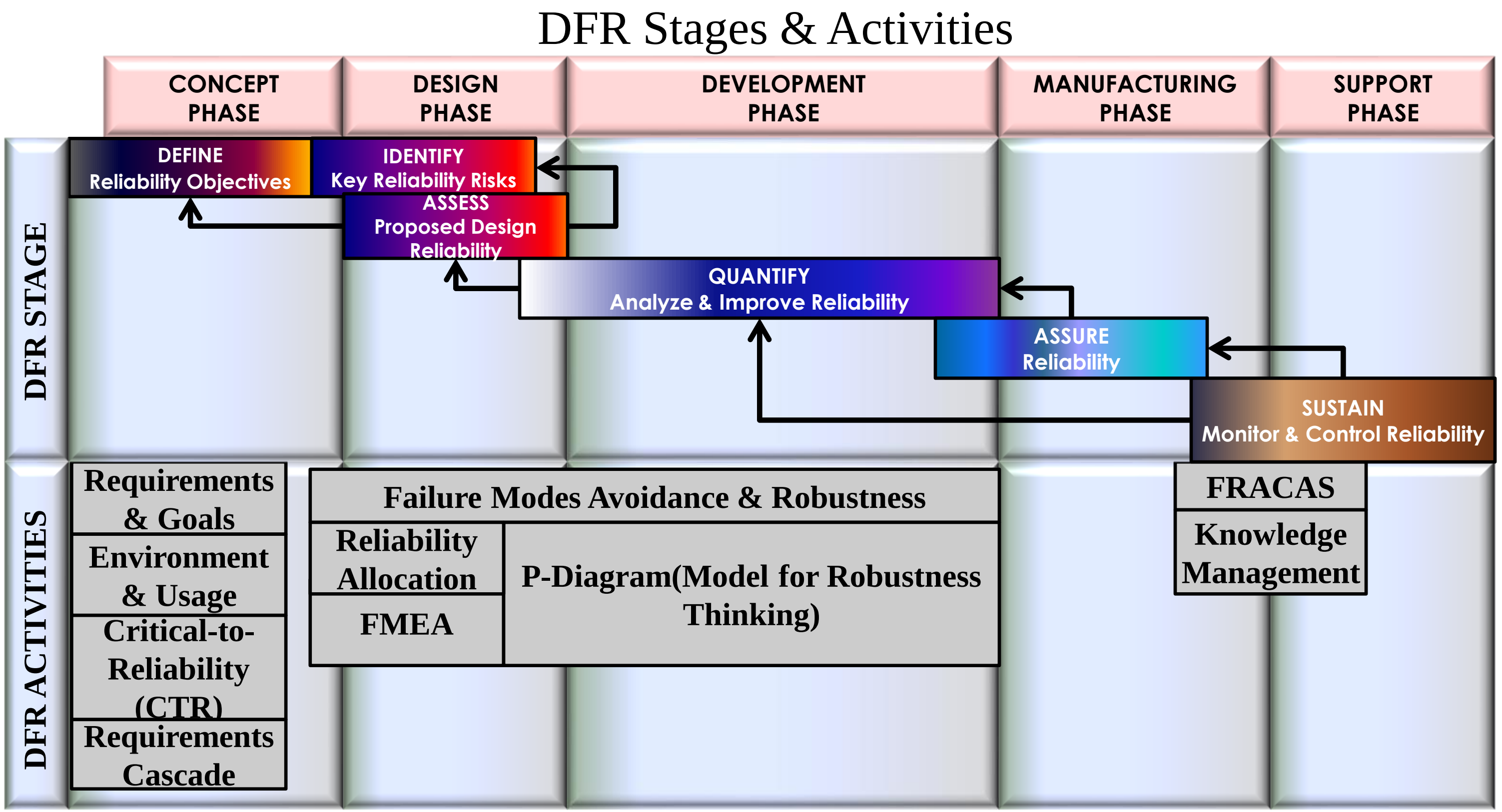
Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**
Customer Reqs. Strategic intent	Conceptual Design	Preliminary Design	Detail Design	Product Verification	Product Validation	Process verification	Launch

Review of Typical DfR Process Used by Companies

DFR Stages & Activities



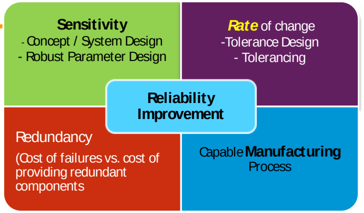
Basic DfR tools

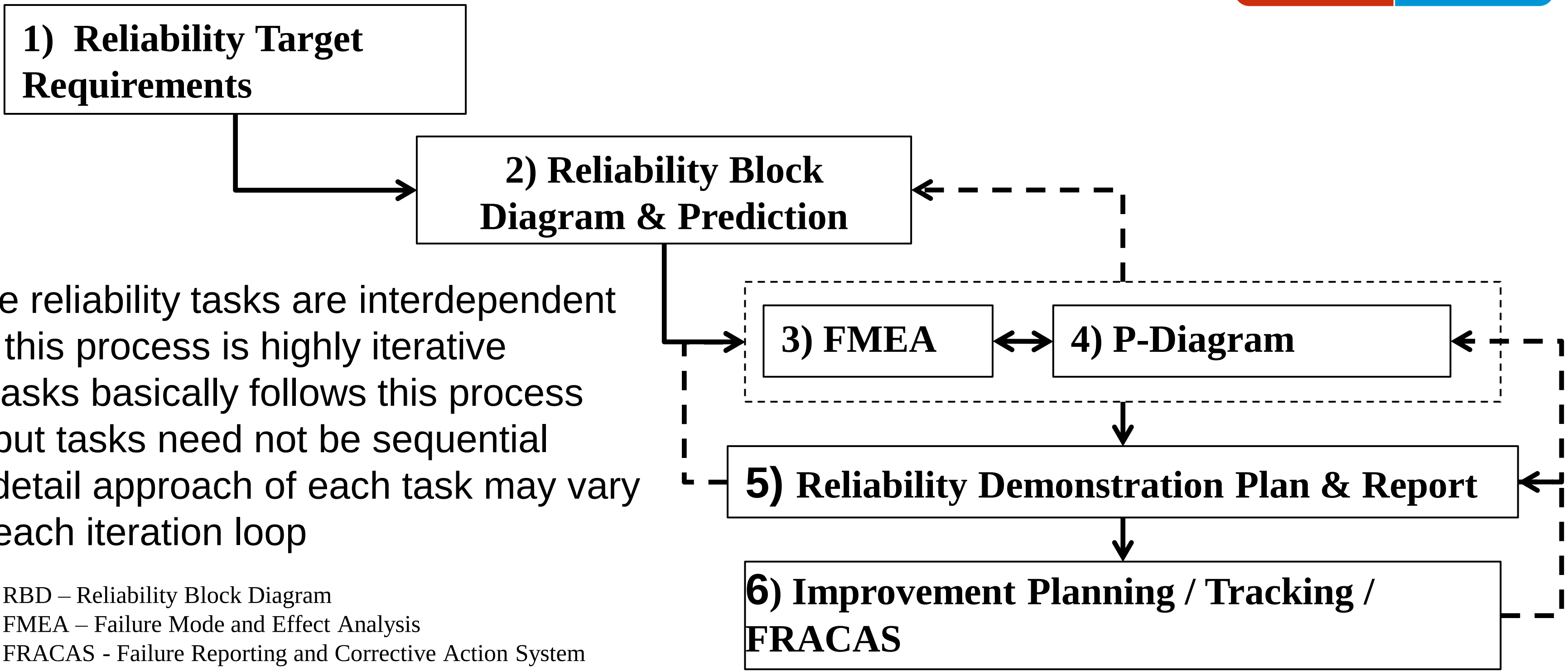


Outline

- Introduction to DFR
- System Engineering process flow (V-Model)
- Variation
- Robustness Thinking in DfR Process
- Alignment to existing Product Development Process
- Factor DfR tasks into product development process
- **Basic reliability tools for common reliability tasks linkage**

Reliability Effort and DfR Basic Tasks Flow

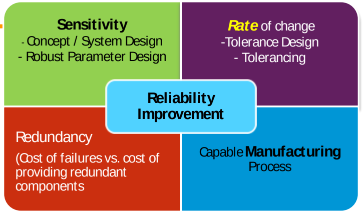




- These reliability tasks are interdependent
- Note this process is highly iterative
- The tasks basically follows this process flow but tasks need not be sequential
- The detail approach of each task may vary with each iteration loop

Note: RBD – Reliability Block Diagram
FMEA – Failure Mode and Effect Analysis
FRACAS - Failure Reporting and Corrective Action System

Example of 6 DfR Basic Tools Application



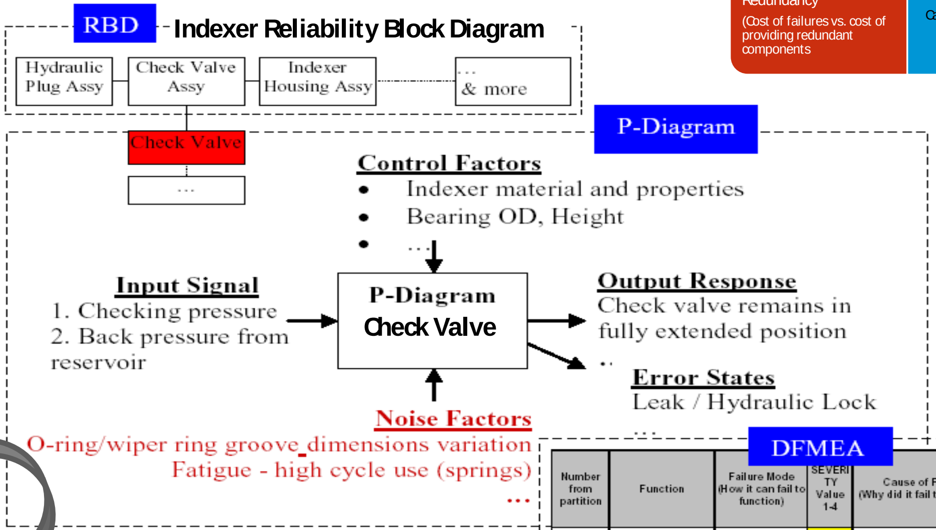
1) Reliability Target Requirements

2) Reliability Block Diagram & Prediction

3) FMEA ⟺ 4) P-Diagram

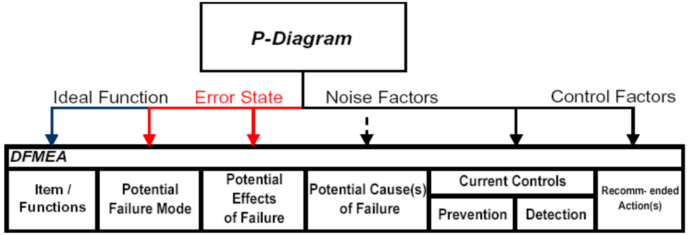
5) Reliability Demonstration Plan & Report

6) Improvement Planning / Tracking / FRACAS



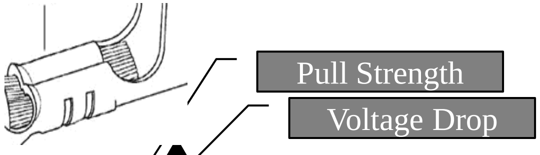
DFMEA

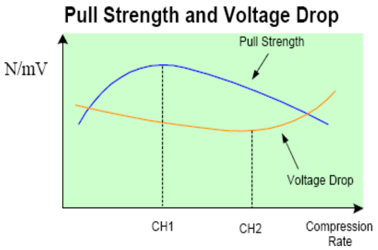
Number from partition	Function	Failure Mode (How it can fail to function)	SEVERITY Value 1-4	Cause of Failure (Why did it fail to function)	OCCURRENCE Value 1-4
Check Valve Assy	Check valve compensates volume in mini-indexer by compressing against spring	Does not compensate volume: Leak / Hydraulic Lock	3	External contamination - debris, foreign material, rust ingress (no mechanism to isolate groove from contamination.	3

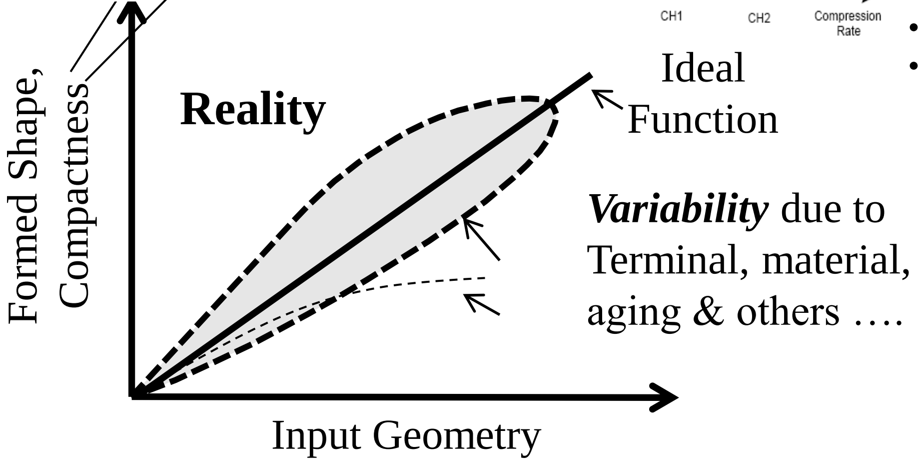


Example of Mechanical Crimped Connector Robust Design

New Approach - Intent: To transfer energy from input energy to form a proper shape.







Quality Problems:

- Poor electrical conduction
- Poor tensile strength
- Poor vibration resistance
- High voltage drop
- Degraded electrical & mechanical int… y
- … etc

Measure of Robustness

$$S / N = \frac{Desired\ Output}{Harmful\ Output}$$

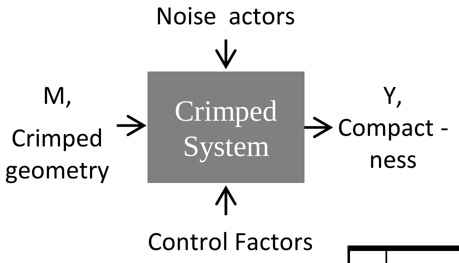
Results:

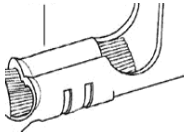
-Pull strength increased
-Voltage drop reduced
- Improved process capability

Focusing on basic function, minimizes the difficulty in improving this problem

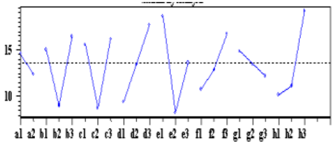
Example of Robust Design (cont'd)

Optimized design in presence of uncontrollable usage environment.

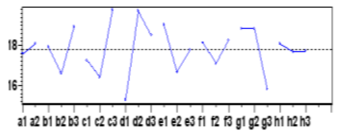


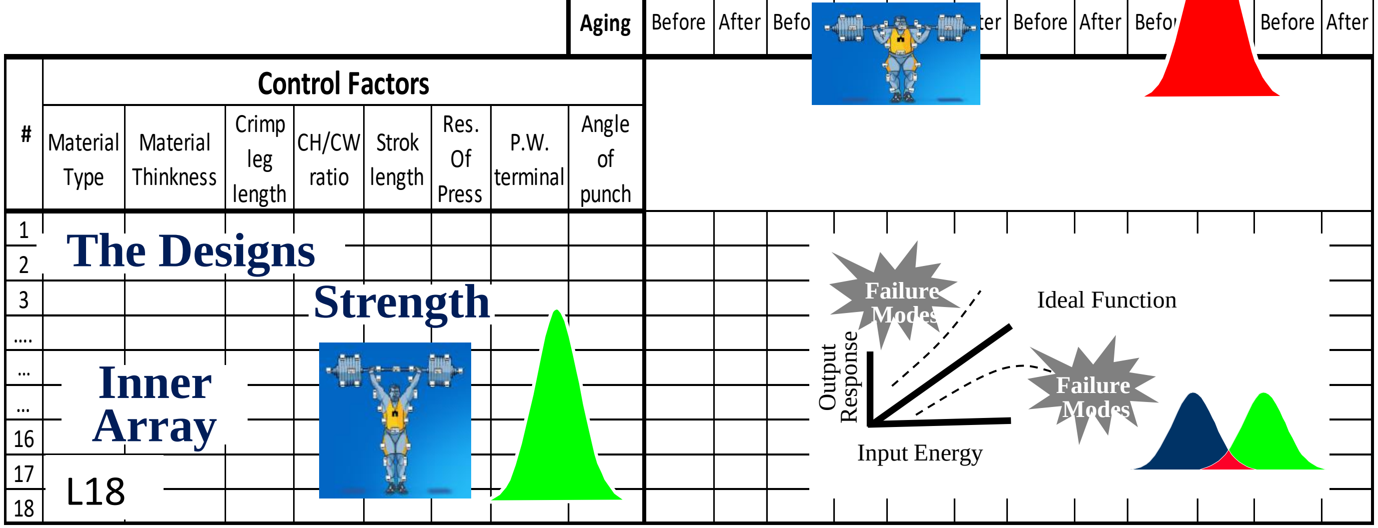


Sensitivity Analysis



SN Ratio Analysis

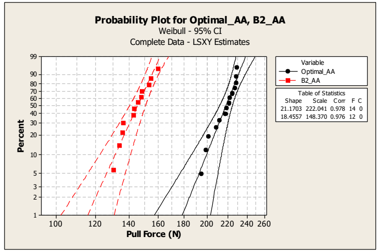




Example of DfR Basic Tools Application (cont'd)

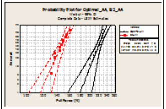
Crimped Connector Reliability Demonstration Plan & Report

RDM Candidates			***RELIABILITY/ROBUSTNESS IMPLEMENTATION***						**VALIDATION EVIDENCE**		
						Noise Factors Present in the Test					
						High Impact Noise Factors					
Key Function /Technology	**High Impact Failure Modes (Soft / Hard)**	**Related Component Subsystem / System**	**Validation Test from RCL**	**Critical Metric**	**Test Target**	**N1. P-to-P variation** **N2. Wear-out / Aging** **N3. Customer Duty Cycle** **N4. External Environment** **N5. System Interactions**	**Metric**	**Range**	**Demonstrated Validation Evidence & Comparison to Prior Design**	**Risk Assess-ment**	**Completion Date**
Example:											
Withstand Force (Pull Strength)	Wires Disconnected	Terminal and Wire strands	Pull strength Life Test	N	150	N1. Different Wire Size N2. Aging	mm Y/N	CSA% Y/N	(see plot below)		4-Jul-99



Example of DfR Basic Tools Application (cont'd)

Crimped Connector Reliability Demonstration Plan & Report

RDM Candidates			*RELIABILITY/ROBUSTNESS IMPLEMENTATION*						VALIDATION EVIDENCE		
						Noise Factors Present in the Test					
						High Impact Noise Factors	Metric	Range			
Key Function /Technology	High Impact Failure Modes (Soft / Hard)	Related Component Subsystem / System	Validation Test from RCL	Critical Metric	Test Target	N1. P-to-P variation N2. Wear-out / Aging N3. Customer Duty Cycle N4. External Environment N5. System Interactions			Demonstrated Validation Evidence & Comparison to Prior Design	Risk Assess-ment	Completion Date
Example:											
Withstand Force (Pull Strength)	Wires Disconnected	Terminal and Wire strands	Pull strength Life Test	N	150	N1. Different Wire Size N2. Aging	mm Y/N	CSA% Y/N			4-Jul-99

Reliability Demonstration Candidates			*RELIABILITY/ROBUSTNESS IMPLEMENTATION*					
						Noise Factors Present in the Test		
						High Impact Noise Factors	Metric	Range
Key Function /Technology	High Impact Failure Modes (Soft / Hard)	Related Component Subsystem / System	Validation Test from Reliability Checklist	Critical Metric	Test Target	N1. P-to-P variation N2. Wear-out / Aging N3. Customer Duty Cycle N4. External Environment N5. System Interactions		

Example of DfR Basic Tools Application (cont'd)

Crimped Connector Reliability Demonstration Plan & Report

RDM Candidates		RELIABILITY/ROBUSTNESS IMPLEMENTATION							VALIDATION EVIDENCE		
						Noise Factors Present in the Test					
						High Impact Noise Factors					
Key Function /Technology	High Impact Failure Modes (Soft / Hard)	Related Component Subsystem / System	Validation Test from RCL	Critical Metric	Test Target	N1. P-to-P variation N2. Wear-out / Aging N3. Customer Duty Cycle N4. External Environment N5. System Interactions	Metric	Range	Demonstrated Validation Evidence & Comparison to Prior Design	Risk Assess-ment	Completion Date
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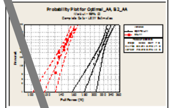
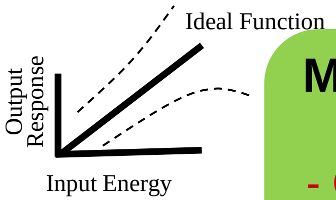
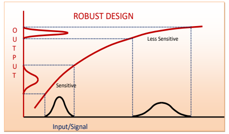
Withstand Force (Pull Strength)	Wires Disconnected	Terminal and Wire strands	Pull strength Life Test	N	150	N1. Different Wire Size N2. Aging	mm Y/N	CSA% Y/N			4-Jul-99

VALIDATION EVIDENCE		
Demonstrated Validation Evidence & Comparison to Prior Design	**Risk Assess-ment**	**Completion Date**

Robust Design for Reliability





Minimize Sensitivity to Noise
- Concept / System Design
- Robust Parameter Design

Reduce Rate of change of product parameters
-Tolerance Design

Robust Design for Reliability

Redundancy
(Cost of failures vs. cost of providing redundant components

Capable **Manufacturing** Process

Benefits of Robust Design

- Shorter time to market
- Lower total development cost
- Customer satisfaction – performance closer to ideal
- Reduced manufacturing cost
- Flexible integration of systems – responsiveness to the market

Important Takeaway

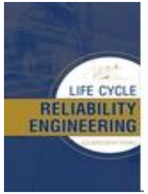
- **Make design insensitive to uncontrollable user environment (Noise)**

- **Early development of robustness is key to proactive quality and reliability Improvement**
  - **Capture, front load noise and manage noise**
  - Gain control of your product performance
  - Optimize robustness – avoid all failure modes

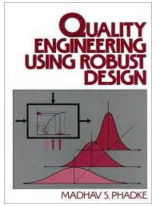
- **Apply Robust design principles at early stages of product design to “forecast” problems and take preventive action.**

Further Reading

Practical Reliability Engineering
by Patrick O'Connor, Andre Kleyner



Life Cycle: Reliability Engineering
by Guangbin Yang



Quality Engineering Using Robust Design

by Madhav S. Phadke

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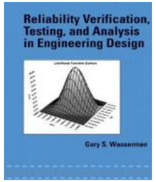
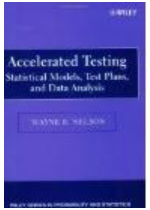
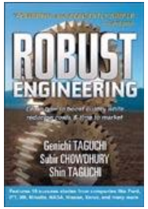


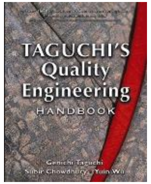
Reliability Verification, Testing, and Analysis in Engineering Design by Gary S. Wasserman



Accelerated Testing: Statistical Models, Test Plans, and Data Analysis (Wiley Series in Probability and Statistics... by Wayne B. Nelson



Robust Engineering: Learn How to Boost Quality While Reducing Costs & Time to Market
by S. Chowdhury
G. Taguchi
S. Taguchi



Taguchi's Quality Engineering Handbook
by Genichi Taguchi, Subir Chowdhury, Yuin Wu

SAE J1211 – "Handbook for Robustness Validation of Automotive E/E Modules", Section 8 - Analysis,
Modeling and Simulations, SAE, April 2009.

Questions?

Thank You!

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