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Using DFSS as an Integrating Framework for MBT&E and DOT&E

Dr. Mark J. Kiemele
Air Academy Associates

NDIA 2011 Test & Evaluation Conference
Tampa, FL
14 March 2011

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11-DFSSLE-3A

Warm-Up Exercise

- **Goal: full concentration on the subject**
- **Eliminate extraneous issues that could inhibit that**
- **Write down the top issue on a plain sheet of paper**
- **Jettison this issue by doing the following:**

  - Design a paper airplane that will help you deposit this issue in the waste basket.

  - Launch your paper airplane at the waste basket from your seating area. You may stand or even move around to launch if you wish.

  - Goal is to put the issue in the waste basket, which is obviously symbolic of "putting the issue away."

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Food for Thought .... True or False?

The systems and products that deliver value to our warfighters are perfectly designed to achieve the results we are getting today.

Session Goals and Objectives

1. **Know what DFSS is and understand that it is a strategy that uses DOE and other powerful methods to design, develop, and field successful systems.**
2. **Understand the DFSS process—Identify, Design, Optimize, Validate (IDOV)—and know that it focuses heavily on the Voice of the Warfighter.**
3. **Know that the DFSS process translates requirements, i.e., task capabilities and system attributes, into measures of effectiveness and measures of performance and then subsequently into design parameters which are then optimized to produce highly capable products and services.**
4. **Relate to some of the powerful tools that are unique to the DFSS process.**
5. **Understand what a transfer function is, be able to comprehend its value, and see that it can be used to develop linkages between Critical Operational Issues (COIs) and measures of performance/effectiveness.**
6. **Comprehend the opportunity for DFSS in your organization with regard to MBT&E and DOT&E.**

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Agenda

- **Introduction and Review**
- **The Motivation for DFSS**
- **The DFSS Process: Identify, Design, Optimize, Validate (IDOV)**
  - The **Identify** Phase
    - –The DFSS Scorecard
    - –Voice of the Customer (VOC)
  - The **Design** Phase
    - –Translating the VOC (Requirements Flowdown)
    - –Concept Generation and Selection
    - –Transfer Functions
    - –Critical Parameter Management
  - The **Optimize** Phase
    - –Multiple Response Optimization
    - –Expected Value Analysis Using Monte Carlo Simulation
    - –Parameter Design
    - –Tolerance Allocation
  - The **Validate** Phase
    - –High Throughput Testing
- **Recap of DFSS with MBT&E and Designing the Test and Evaluation**
- **DFSS Success Stories**

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Introduction and Review

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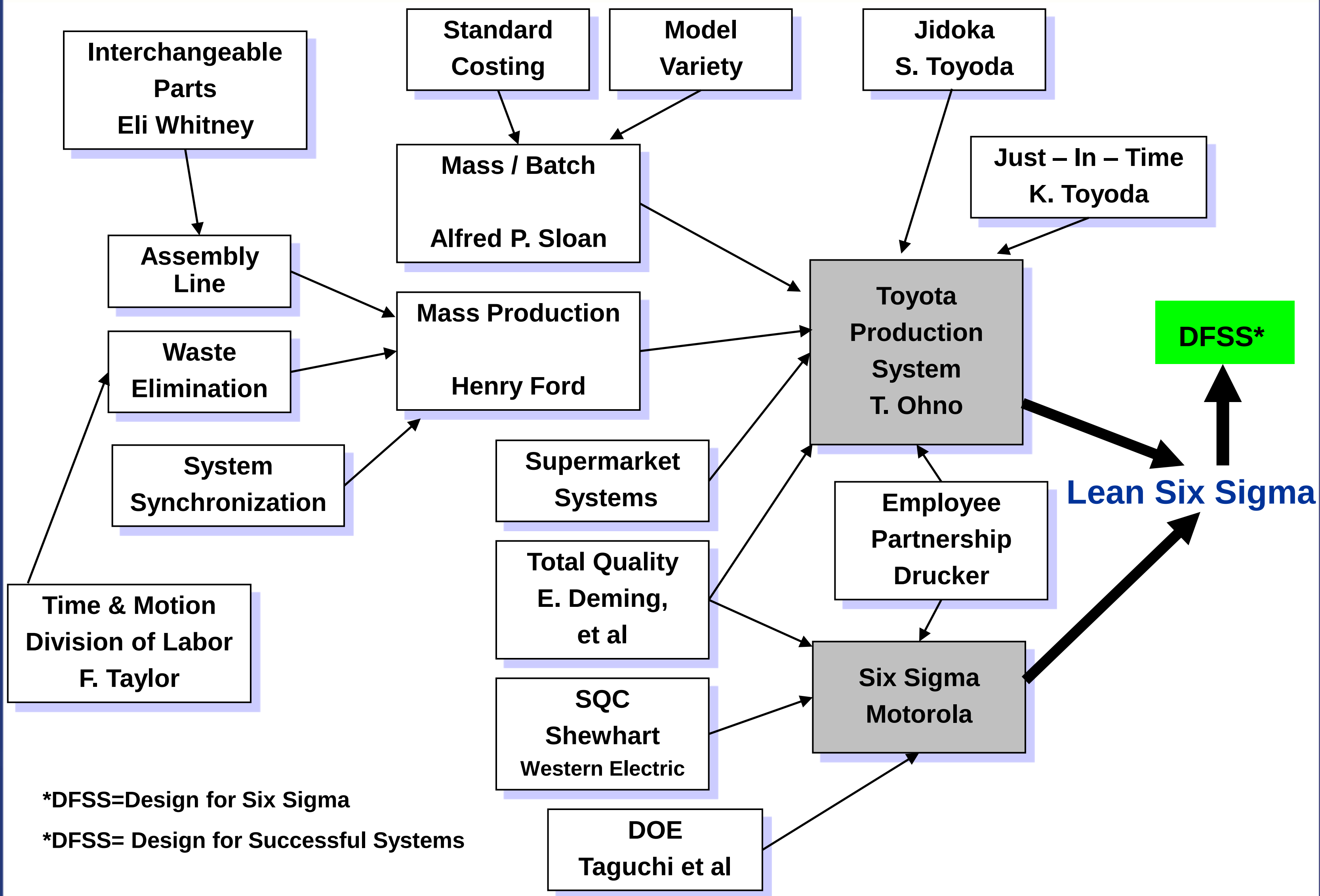
Performance Improvement Evolution



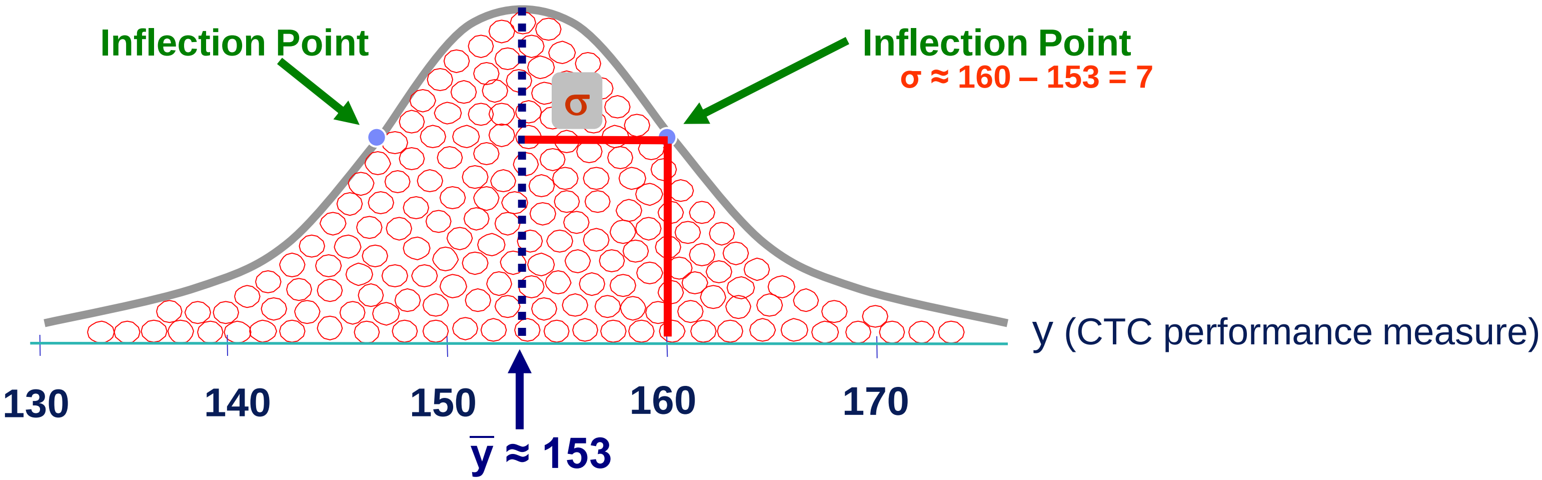
*DFSS=Design for Six Sigma

*DFSS= Design for Successful Systems

Graphical Meaning of $\bar{y}$ and σ

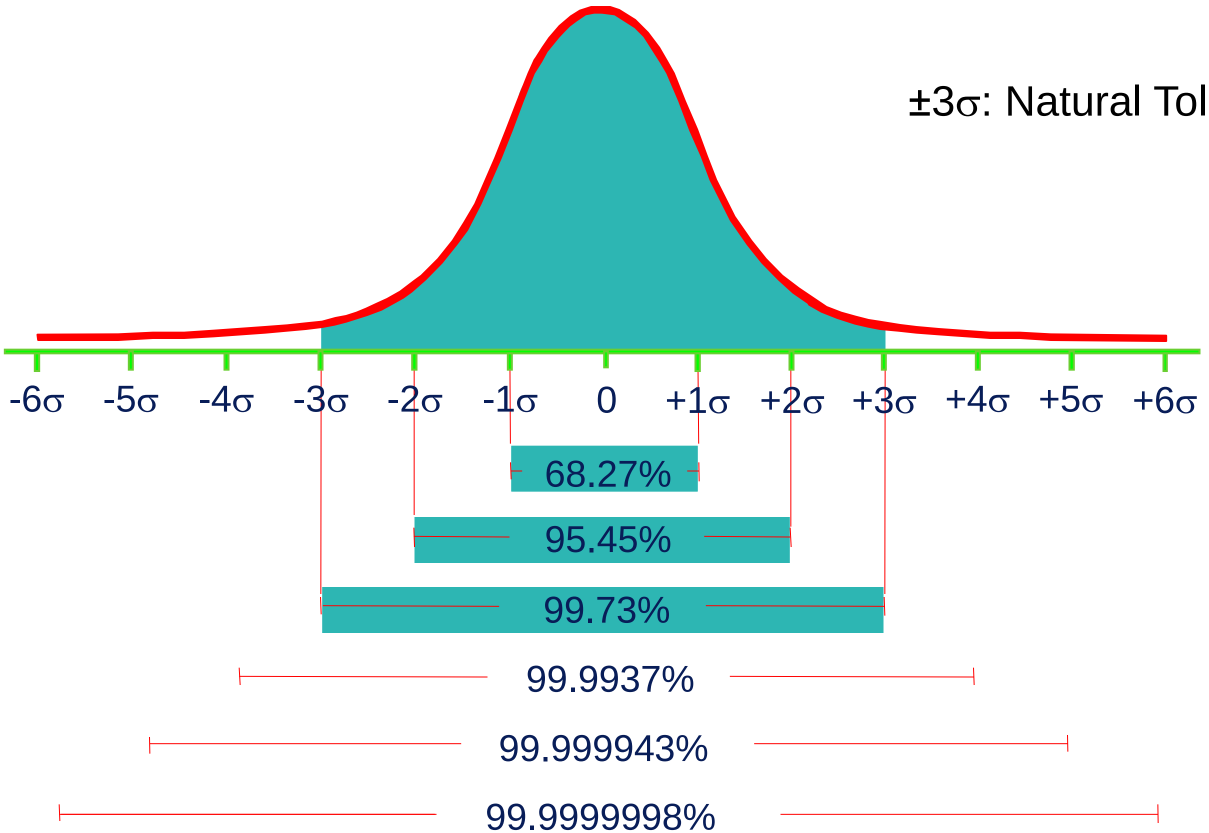
$\bar{y}$ = Average = Mean = Balance Point

σ = Standard Deviation



σ ≈ average distance of points from the centerline

Graphical View of Variation

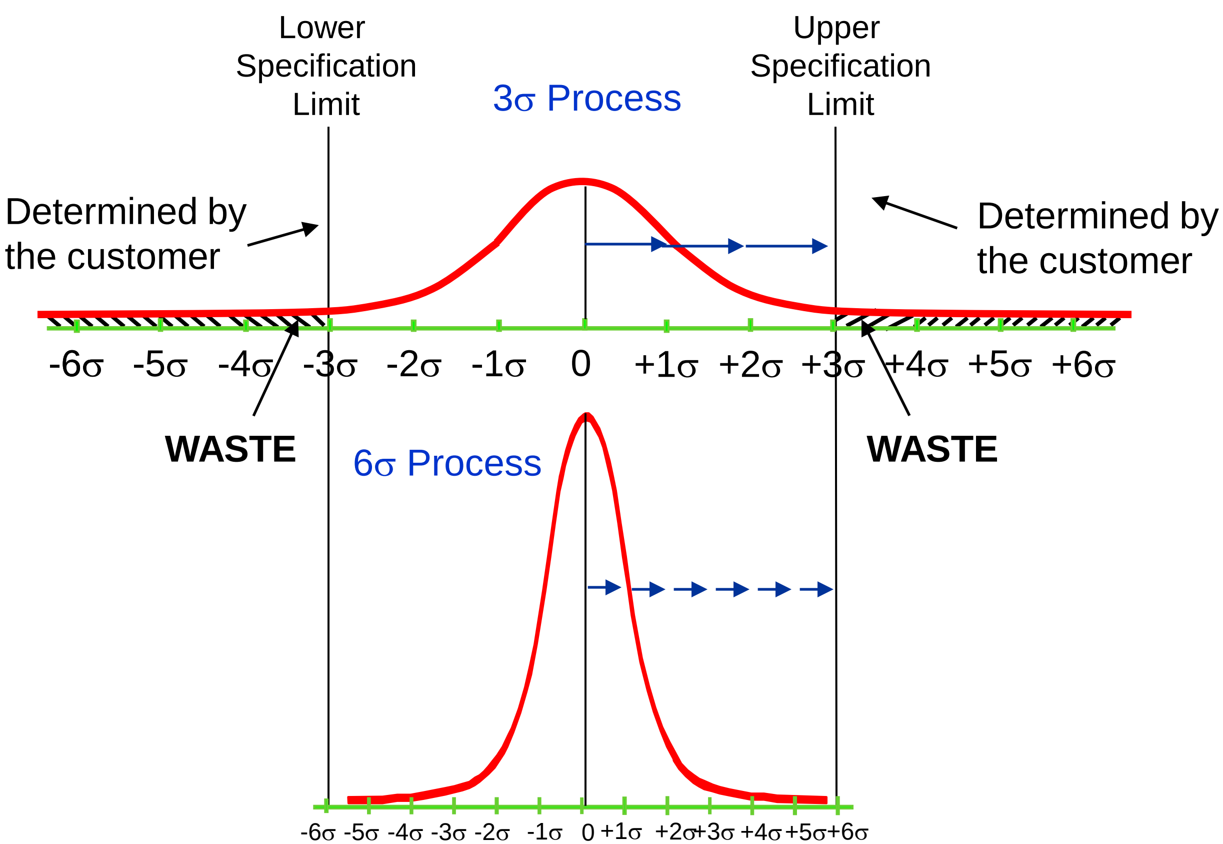


Typical Areas under the Normal Curve

Graphical View of Variation and Performance Capability

The Sigma rating/capability of a process performance measure is the result of comparing the **Voice of the Process** with the **Voice of the Customer**, and it is defined as follows:

The **number of Sigmas** between the center of a process performance measure's distribution and the nearest specification limit



<u>3σ Process Centered</u>

- Process is WIDER than the specifications, causing waste and cost of poor quality

<u>6σ Process Centered</u>

- Process FITS well within the specifications, so even if the process shifts, the values fall well within tolerances

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Sigma Ratings Measure Process Capability

Sigma Capability is a measure of quality. It compares the Voice of the Process with the Voice of the Customer and is correlated to the defect rate. It is computed from DPMO.

Yield is the probability that whatever we are producing (manufactured part, PO, shipped part, etc.) will pass through the entire process without rework and without defects.

σ Capability*	DPMO*	RTY
2	308,537	69.1%
3	66,807	93.3%
4	6,210	99.4%
5	233	99.97%
6	3.4	99.99966%
Process Capability	Defects per Million Opportunities	Rolled Throughput Yield

Six Sigma is a standard of Excellence.
It means less than 4 Defects per Million Opportunities.

* Assumes a 1.5 sigma shift in average if the performance measure is normally distributed

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Relationship Between Lean, Six Sigma and DFSS

Perfect → Six Sigma

N (Simplify)
NE
E (Perfect)

Lean ↑ Simplify

OVERALL YIELD vs SIGMA
(Distribution Shifted ±1.5σ)

# of Parts (Steps)	±3σ	±4σ	±5σ	±6σ
1	93.32%	99.379%	99.9767%	99.99966%
7	61.63	95.733	99.839	99.9976
10	50.08	93.96	99.768	99.9966
20	25.08	88.29	99.536	99.9932
40	6.29	77.94	99.074	99.9864
60	1.58	68.81	98.614	99.9796
80	0.40	60.75	98.156	99.9728
100	0.10	53.64	97.70	99.966
150	- - -	39.38	96.61	99.949
200	- - -	28.77	95.45	99.932
300	- - -	15.43	93.26	99.898
400	- - -	8.28	91.11	99.864
500	- - -	4.44	89.02	99.830
600	- - -	2.38	86.97	99.796
700	- - -	1.28	84.97	99.762
800	- - -	0.69	83.02	99.729
900	- - -	0.37	81.11	99.695
1000	- - -	0.20	79.24	99.661
1200	- - -	0.06	75.88	99.593
3000	- - -	- - -	50.15	98.985
17000	- - -	- - -	1.91	94.384
38000	- - -	- - -	0.01	87.880
70000				78.820
150000				60.000

DFSS

Use for Benchmarking

Source: Six Sigma RESEARCH INSTITUTE Motorola University Motorola, Inc.

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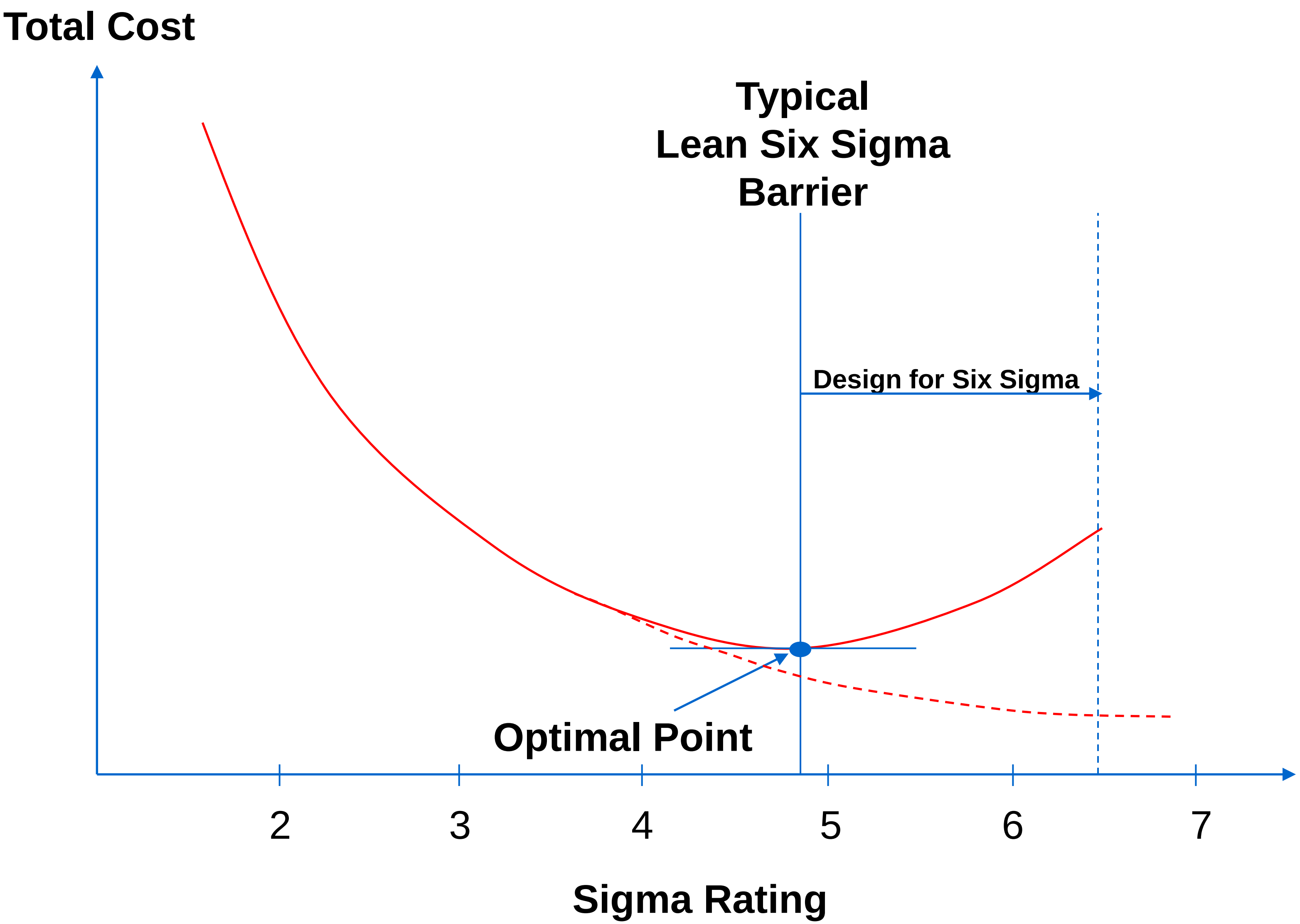
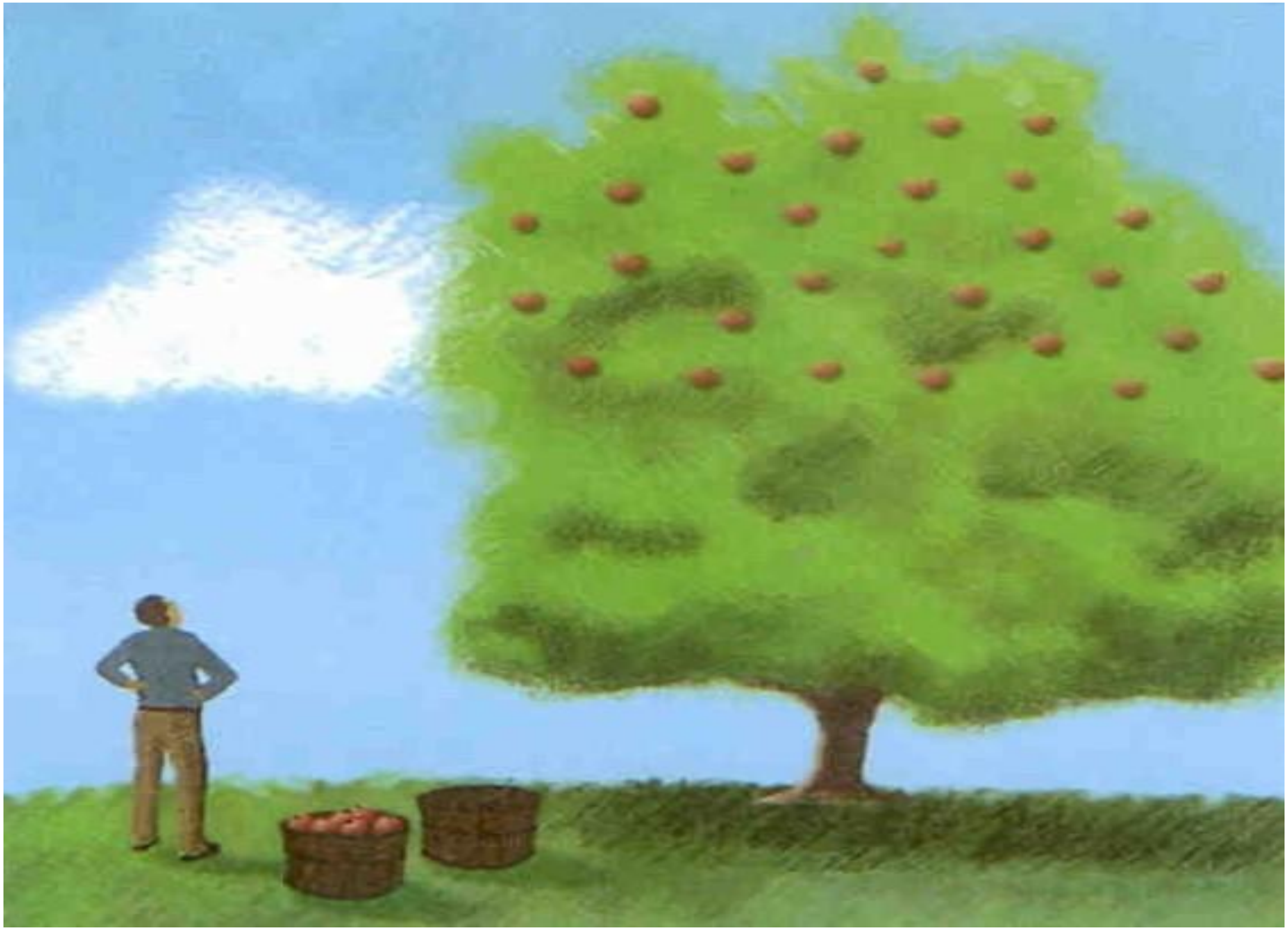
The Motivation for DFSS

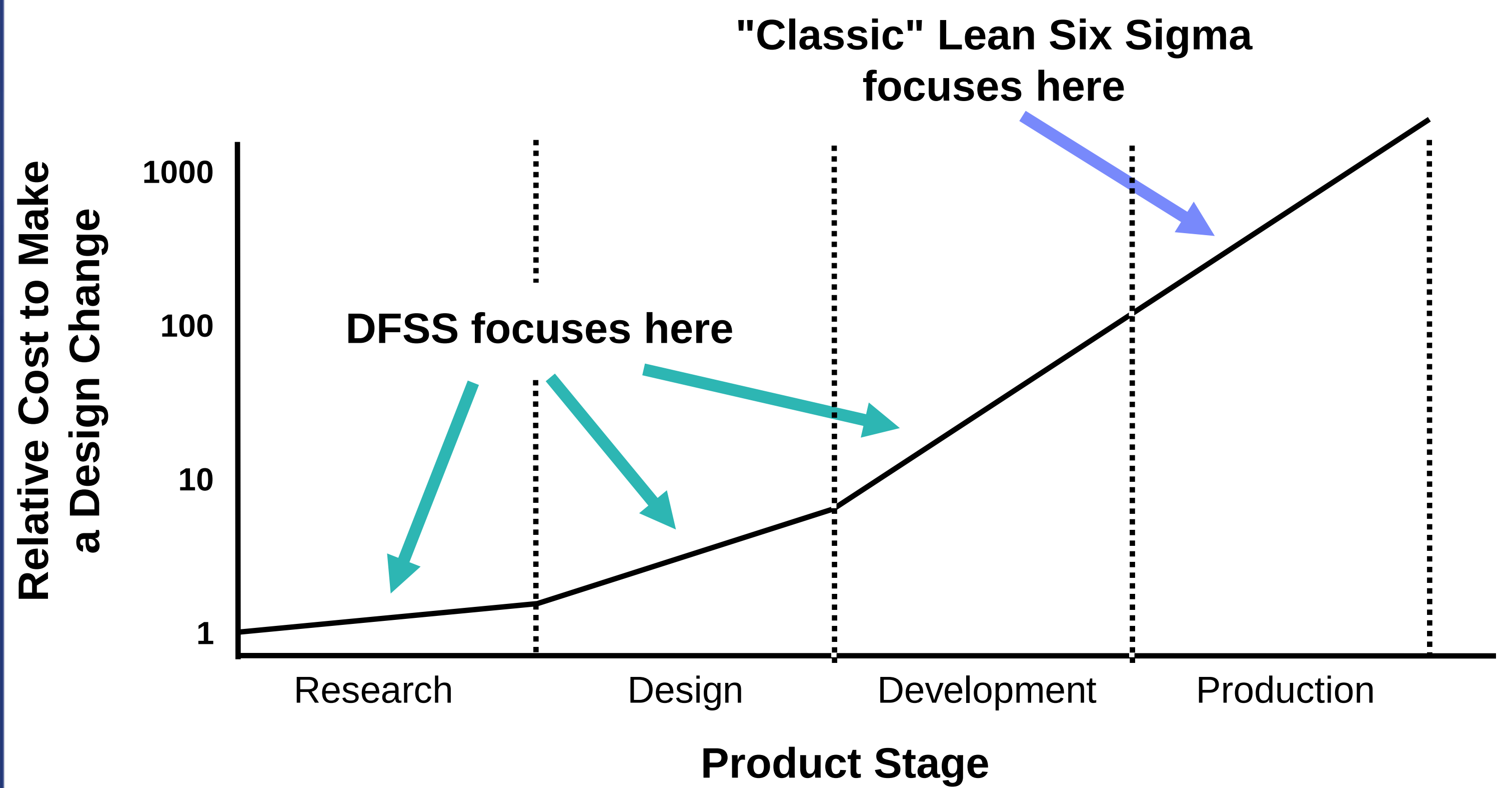
What Have We Learned from LSS (DMAIC)?



DFSS: Getting to the Next Level (the high hanging fruit)



Why DFSS



- **Gain knowledge when costs are lowest**
- **Design in quality right from the start**

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DFSS Goals

- ***Reduce Cycle Time in the Design and Development Process***
- ***Reduce the Time to Money (TTM)***
- ***Reduce the Cost of Poor Quality***
- ***Improve Predictability of QCD (Quality, Cost, Delivery)***

General Electric Testimonial (Dr. Norm Kuchar*, GECRD, Oct 2011)

- **Quality increases of at least +1σ at launch over previous designs**
- **Time to Market decrease by at least 25% over previous launches**
- **Cost savings due to total resources utilized in the 20-40% range**

* Norm was responsible for the worldwide deployment of GE's DFSS initiative.

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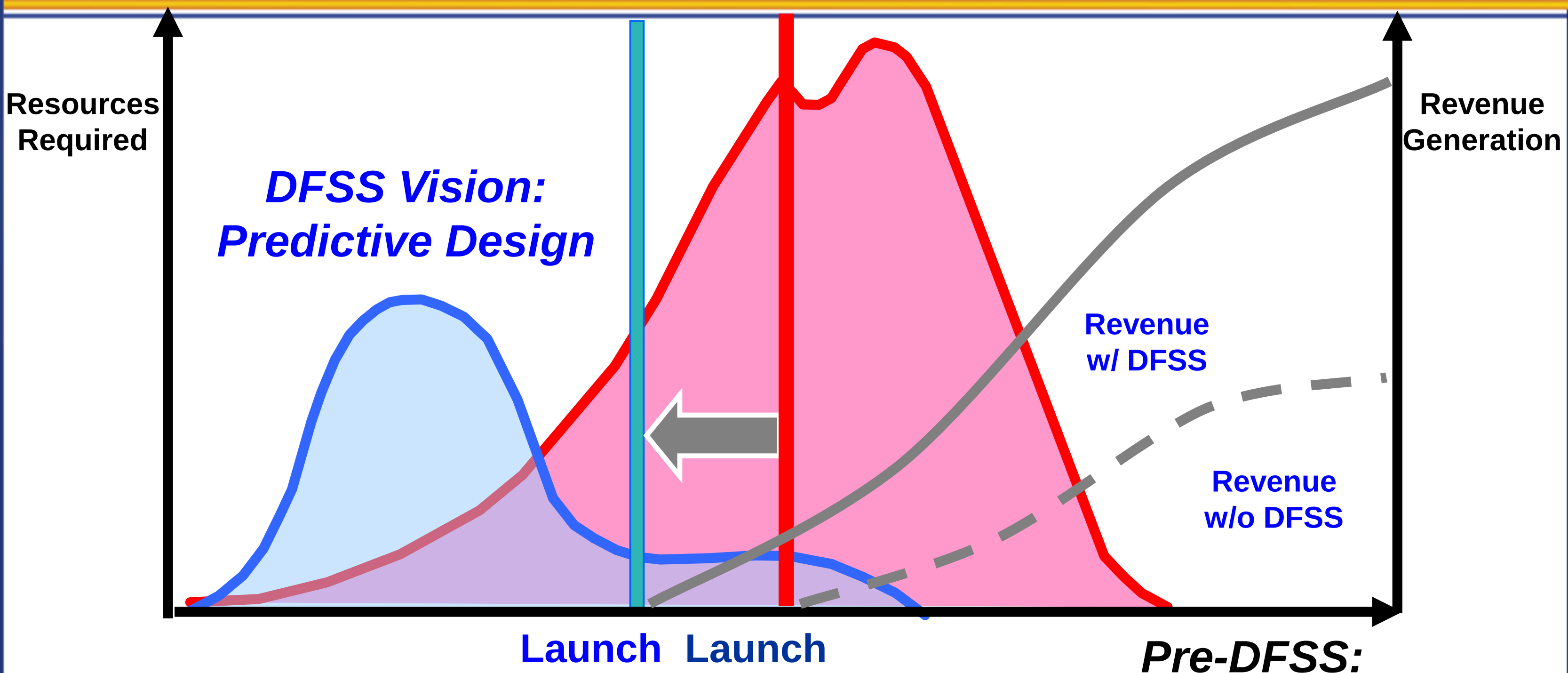
The Benefits of DFSS



- Early problem identification; solution when costs low
- Faster market entry: earlier revenue stream, longer patent coverage
- Lower total development cost
- Robust product at market entry: delighted customers
- Resources available for next game-changer

- Unhappy customers and employees
- Unplanned resource drain
- Skyrocketing costs
- Next product compromised

- **Upfront investment is most effective and efficient**
- **Show customers highly capable products right from the start**

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The Vision of DFSS

From

- **Evolving design requirements**
- **Extensive design rework**
- **Product performance assessed by "build and test"**
- **Performance and producibility problems fixed <u>after</u> product in use**
- **Quality "tested in"**

To

- **Disciplined requirements flowdown**
- **Controlled design parameters**
- **Product performance modeled and simulated**
- **<u>Designed</u> for robust performance and producibility**
- **Quality "designed in"**

- **Lean Six Sigma (DMAIC) fixes known problems.**
- ***DFSS prevents unknown problems from occurring.***

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Infamous Quote

“As we know, there are known knowns. These are the things we know we know.

We also know there are known unknowns.
That is to say we know there are
some things we do not know.

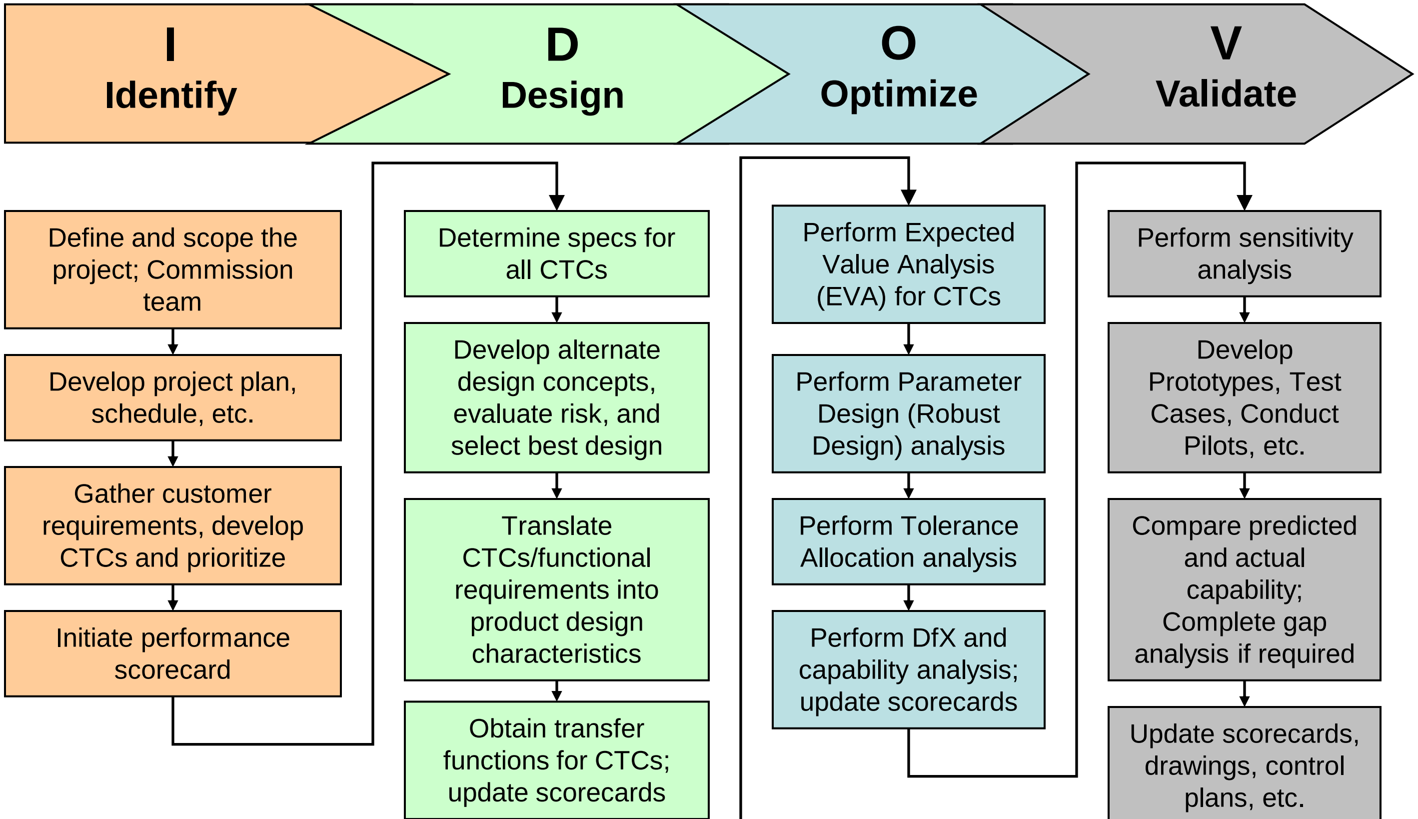
But there are also unknown unknowns, the ones we don’t know we don’t know.”

Donald Rumsfeld
Department of Defense news briefing
February 12, 2002

Overview of the DFSS Process

Identify-Design-Optimize-Validate (IDOV*) Model

** The **IDOV** four-phase DFSS process originated with Dr. Norm Kuchar at GE CRD and is used with permission.*



Key Deliverables:

- strategic plan
- benchmarking results
- customer requirements; prioritized, measurable CTCs (HOQ #1)
- Initial performance scorecard

- Design concepts and selection results
- Requirements flowdown
- Prioritized product design characteristics (HOQ #2)
- Design risk assessments
- Transfer functions
- Updated scorecards

- Capability and reliability studies
- X-ability assessment
- Optimized design
- Capability analysis
- Tolerances for key Xs
- Updated scorecards (capability flowup)

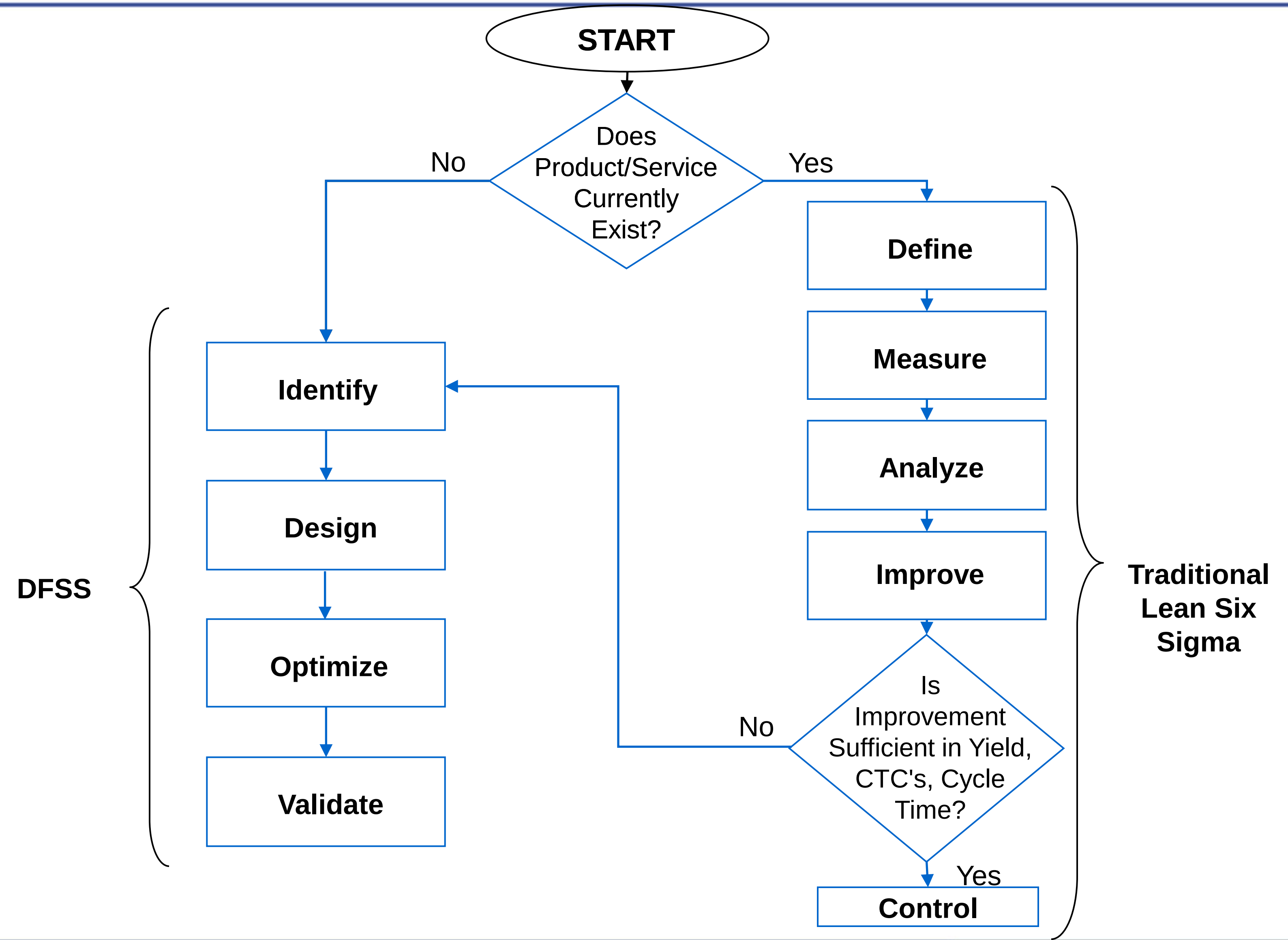
- Sensitivity analysis
- Pilots / prototypes and capability analysis
- Validated processes and products
- Updated scorecards
- Control plan

Methods and Tools Used in DFSS

Identify	Design	Optimize	Validate
Project or Study Charter	Assign Specifications to CTC's	Histogram	***Sensitivity Analysis***
Strategic Plan	***Axiomatic Design***	***Distributional Analysis***	***Gap Analysis***
Cross-Functional Team	***Critical Parameter Mgt.***	***Empirical Data Distribution***	FMEA
Voice of the Customer	Formulate Design Concepts	***Expected Value Analysis (EVA)***	Fault Tree Analysis
Customer Retention Grid	***Pugh Concept Generation***	***Adding Noise to EVA***	Control Plan
Benchmarking	***TRIZ***	Non-Normal Output Distributions	PF/CE/CNX/SOP
KANO's Model	FMEA	Design of Experiments	Run/Control Charts
Questionnaires	Fault Tree Analysis	***Multiple Response Optimization***	Mistake Proofing
Focus Groups	Brainstorming	***Robust Design Development***	MSA
Interviews	QFD	***Using S-hat Model***	Reaction Plan
Internet Search	Scorecard	***Using Interaction Plots***	***High Throughput Testing***
Historical Data Analysis	***Transfer Function***	***Using Contour Plots***	
Design of Experiments	Design of Experiments	***Parameter Design***	
Quality Function Deployment	***Deterministic Simulators***	***Tolerance Allocation***	
Pairwise Comparison	***Discrete Event Simulation***	***Design For Manufacturability and Assembly***	
Analytical Hierarchy Process	Confidence Intervals	Mistake Proofing	
Performance Scorecard	Hypothesis Testing	Product Capability Prediction	
Flow Charts	MSA	***Part, Process, and SW Scorecard***	
FMEA	Computer Aided Design	***Risk Assessment***	
Visualization	***Computer Aided Engineering***	***Reliability***	
		Multidisciplinary Design Optimization (MDO)	

*Unique to DFSS

DFSS vs DMAIC



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Project Selection: "DMAIC" or "DFSS"?

- In general,
  - "DMAIC" approach and tools work best when goal is to improve an existing product or process, with baseline performance metrics.
  - "DFSS" approach and tools work best when goal is to design a new product or process, with no baseline performance metrics available, or to redesign an existing product or process that is not meeting the performance requirements.
- Many projects contain elements of both; use appropriate tools, without concern about "purity" of approach

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The Identify Phase

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The DFSS Process: Identify, Design, Optimize, Validate

– ***The Identify Phase***
  – ***The DFSS Scorecard***
  – ***Voice of the Customer (VOC)***

– The **Design** Phase
  – Translating the VOC (Requirements Flowdown)
  – Concept Generation and Selection
  – Transfer Functions
  – Critical Parameter Management

– The **Optimize** Phase
  – Multiple Response Optimization
  – Expected Value Analysis Using Monte Carlo Simulation
  – Parameter Design
  – Tolerance Allocation

– The **Validate** Phase
  – High Throughput Testing

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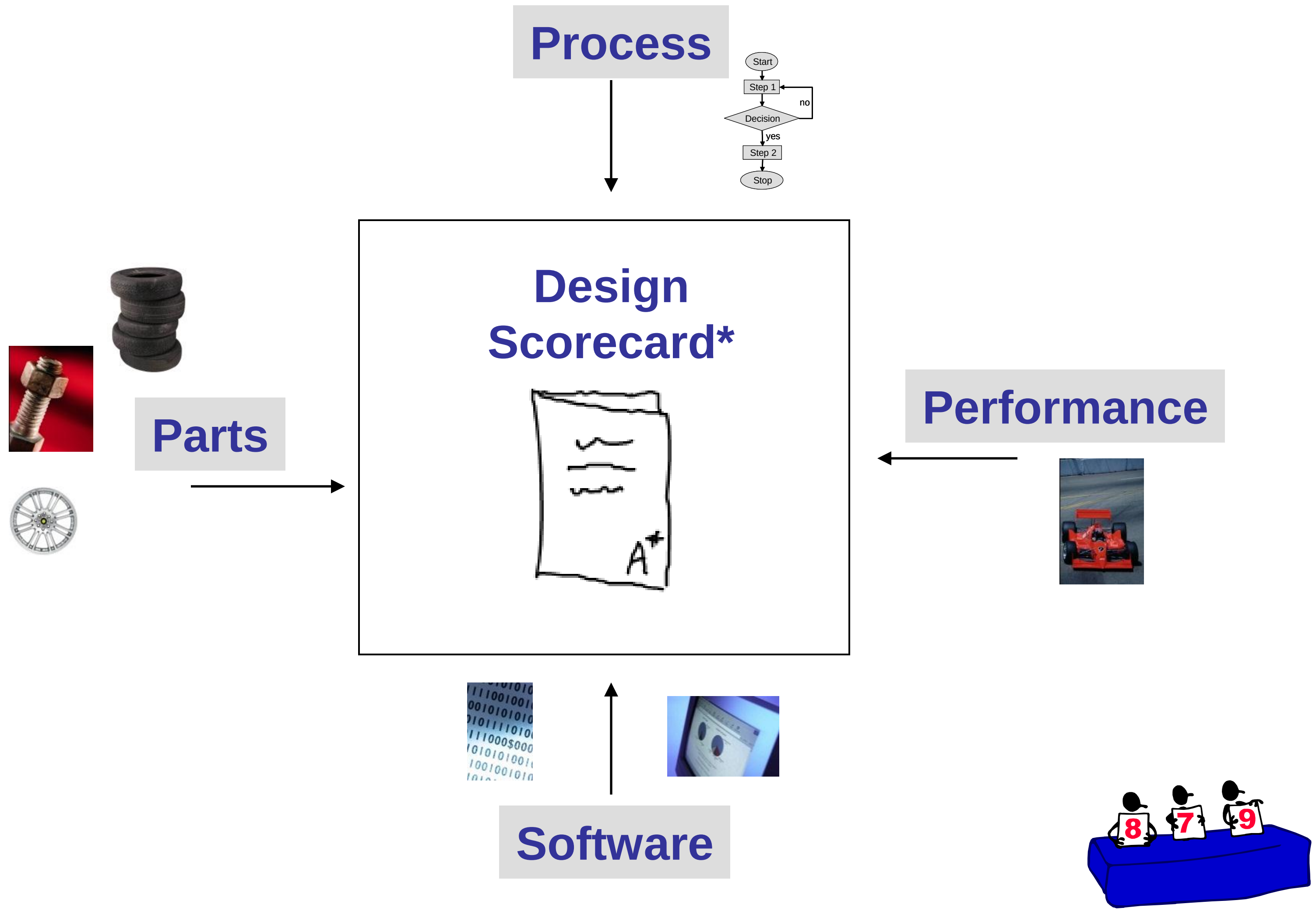
DFSS Scorecard and its Components



* The DFSS Design scorecard concept originated at Texas Instruments (Defense Systems and Electronics Group) in the early 1990s, and has been adapted and used by DFSS practitioners over the past decade(s).

Examples of Parts, Process, Performance

	Refrigerator	Engraved Nameplate	Statapult®
PARTS	*shelves*	*metal plate*	*pull-back arm*
	drawers	*sealant*	*pins*
	evaporator		*cup*
	thermostat		*rubber band*
PROCESS	*weld sheet metal*	*align plate*	*attach protractor*
	attach handle	*engrave*	*attach cup*
	attach handle	*apply sealant*	*drill holes*
	spray protective coating		*assemble side panels to base*
PERFORMANCE	*noise level*	*plate flatness*	*ball/cup fit*
	cooling speed	*engraving quality*	*lateral dispersion*

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Examples* of Scorecard Entries for MBT&E

Task	*Measure*
Employ Lethal Fire Support	Time to Target (< 15 min)
Conduct Lethal Direct Fires	Positive Control Range (> 50 nm) Pssk (> .80)

System Attribute	*Measure*
Aircraft TDL	link range (> 60 nm)
Provide Lethal Effects	Pk/h (> .95)
Guide Munition	Ph/s (> .90)

* These examples are taken from Chris Wilcox's MBT&E Tutorial (page 23) at NDIA T&E 2010.

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Scorecard Construction

- **The scorecard is broken down into 4 major areas:**
  - **Parts**
  - **Process**
  - **Performance**
  - **Software**

- **A total dpu is computed for each of the four areas**

- **The 4 dpu's are summed to obtain a total (overall) dpu for the entire product**

Part DPU + Process DPU + Performance DPU + Software DPU

= Total DPU

- **First Pass Yield (FPY) is estimated using the approximation:**

$$FPY = e^{-dpu}$$

Scorecard Example (Nameplate)

Part Scorecard

				Continuous Variable						Sample Size Known		ppm Only
#	Part Name	DPU	Qty	Target	Mean	Std Dev	LSL	USL	UOM	Sample Size	# Defective	ppm
1	plate thickness	0.0001083	1	0.0625	0.0614	0.008	0.03125	0.09375	in.			
2	plate width	0.0004306	1	1.5	1.51	0.015	1.44	1.56	in.			
3	sealant	0.00005	1									50

Process Scorecard

					Continuous Variable						Sample Size Known		ppm Only
#	Process Step	DPU	Qty	Opps	Target	Mean	Std Dev	LSL	USL	UOM	Sample Size	# Defective	ppm
1	align plate in fixture	0.0005000	1	1									500
2	engrave	0.0020000	1	1							1500	3	
3	apply sealant	0.0073333	1	1							1500	11	

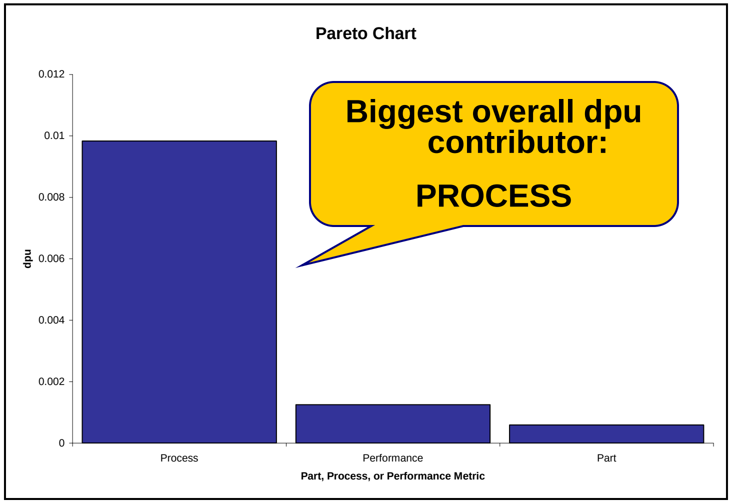
Performance Scorecard

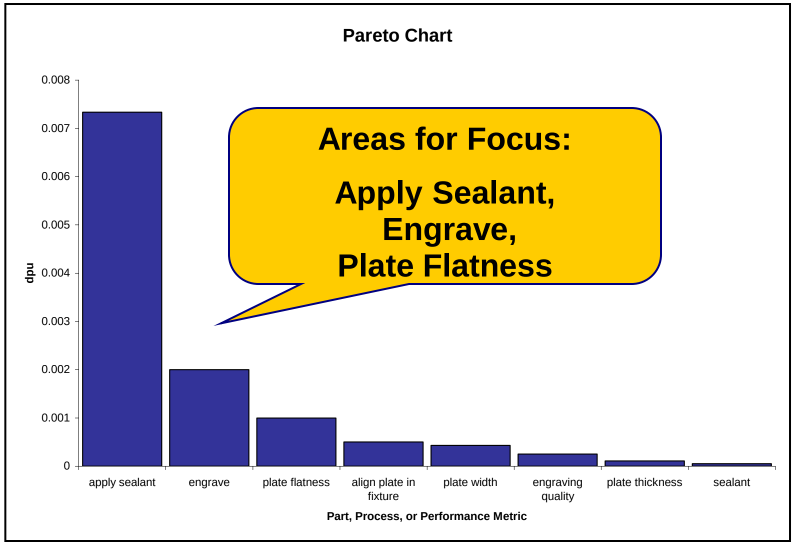
				Continuous Variable						Sample Size Known		ppm Only
#	Performance	DPU	Qty	Target	Mean	Std Dev	LSL	USL	UOM	Sample Size	# Defective	ppm
1	plate flatness	0.0009977	1		0.091	0.011		0.125	in.			
2	engraving quality	0.00025	1							4000	1	

Scorecard Example (Nameplate, cont.)

Overall Scorecard (Roll-Up)

	Scorecard Summary					
	# Steps/Parts	Total dpu	Yield	dpmo	ST Sigma	LT Sigma
Part	3	0.000589	99.94%	196.31	5.04	3.54
Process	3	0.009833	99.02%	3,277.78	4.22	2.72
Performance	2	0.001248	99.88%	623.86	4.73	3.23
Software	0					
Total	**8**	**0.011669983**	**98.84%**	**1458.748**	**4.476**	**2.976**





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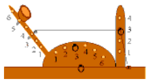
Statapult Scorecard Summary



Scorecard Summary	# Steps/Parts	Total dpu	Yield	dpmo	ST Sigma	LT Sigma
Part	34	0.225959	79.78%	6,645.86	3.98	2.48
Process	77	0.260752	77.05%	3,386.39	4.21	2.71
Performance	4	0.010783	98.93%	2,695.69	4.28	2.78
Software	0					
Total	115	0.497494041	60.81%	4,326.035	4.126	2.626

				Continuous Variable						Sample Size Known		ppm Only
#	Part Name	DPU	Qty	Target	Mean	Std Dev	LSL	USL	UOM	Sample Size	# Defective	ppm
1	Base	2.8666E-07	1	0.75	0.76	0.012	0.68	0.82	inches			
2	Side Plates	0.13137951	2	0.75	0.747	0.027	0.7	0.8	inches			
3	Cup	0.05714286	1							140	8	
4	Cup Screw	0.000014	1									14
5	Front Fixed Arm	0.00147276	1	0.75	0.745	0.015	0.7	0.8	inches			
6	Pull Back Arm Length	9.0705E-05	1	14.5	14.55	0.12	14	15	inches			
7	Pull Back Arm Width	0.00095062	1	0.75	0.752	0.015	0.7	0.8	inches			
8	Angle Scale	0.0014	1							10000	14	
9	Angle Pointer	0.00015	1							20000	3	
10	Removable Pins	0.00006	3									20
11	Nameplate	0.00025	1									250
12	Eye Bolt	0.0004995	1							2002	1	
13	Wing Nut	0.002	2							2000	2	
14	Stop Pad	0.000031	1									31
15	Ball	3.1672E-05	1	1.5	1.51	0.01	1.45	1.55	inches			
16	Rubber Band	0.0001	1									100
17	Metal Pins	0.00039992	2							10002	2	
18	Wooden Peg	0.00987425	1	0.375	0.373	0.0075	0.355	0.395	inches			
19	Wood Screw	0.00008	8									10
20	Plastic Cap	0.000032	2									16
21	Adhesive	0.02	1							100	2	

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Statapult Scorecard Summary (cont.)

#	Process Step	DPU	Qty	Opps	Continuous Variable Target	Mean	Std Dev	LSL	USL	UOM	Sample Size Known Sample Size	# Defective	ppm Only ppm
1	drill cb through holes	0.0039000	6	2									650
2	drill non-cb through holes	0.0072000	18	1									400
3	drill cs holes	0.0040000	1	2							2000	8	
4	drill blind holes	0.0270000	9	2							1000	3	
5	assemble fixed arm and side	0.0000000	1	6		7.8	0.045	5		N			
6	install wood screws	0.1538462	2	1							26	2	
7	install caps	0.0080000	2	1							1000	4	
8	install wooden peg	0.0006667	1	1							3000	2	
9	install angle scale	0.0196078	1	2							102	2	
10	attach angle pointer	0.0020000	1	2							1000	2	
11	attach rubber stop pad	0.0013316	1	2							1502	2	
12	install cup on arm	0.0010000	1	1									1000
13	install removable pins	0.0002000	2	1							10002	1	
14	insert arm between side plat	0.0020000	1	2							1000	2	
15	assemble rubber band	0.0200000	1	3							150	3	
16	attach name plate	0.0100000	1	2							100	1	

#	Performance	DPU	Qty	Continuous Variable Target	Mean	Std Dev	LSL	USL	UOM	Sample Size Known Sample Size	# Defective	ppm Only ppm
1	gap	0.006252391	1		0.06	0.014	0.005	0.095	inches			
2	distance	0.003830381	1		162	4.5	150		inches			
3	life	0.0002	1									200
4	wood grain quality	0.0005	1							4000	2	

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Who is known to have said this?

If we're not keeping score,

we're only practicing.

Hint: a famous football coach

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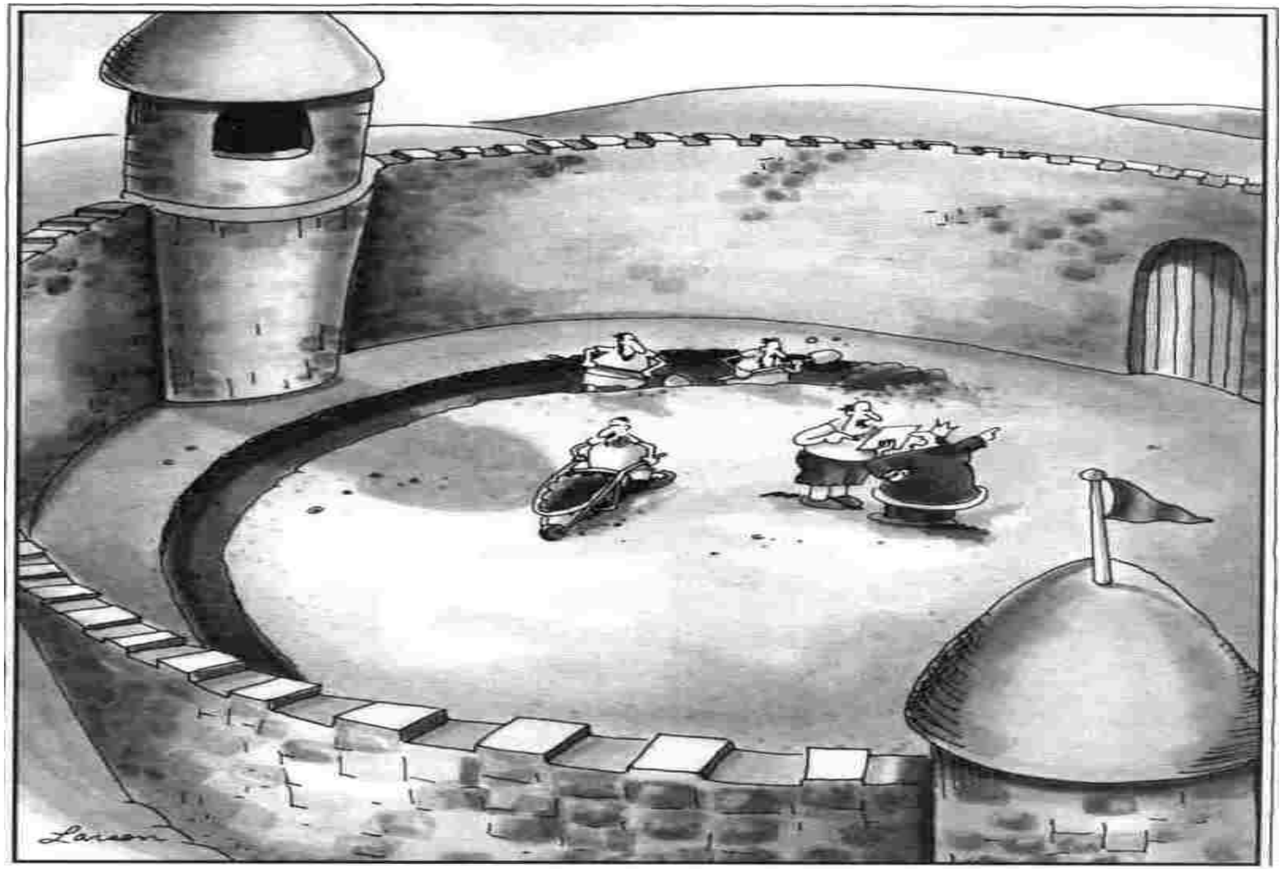
Understanding the Voice-of-the-Customer (VOC)



Suddenly, a heated exchange took place
between the king and the moat contractor.

Source: The Far Side

The Far Side Millennium Off-the-Wall Calendar 2000

Far Works, Inc.

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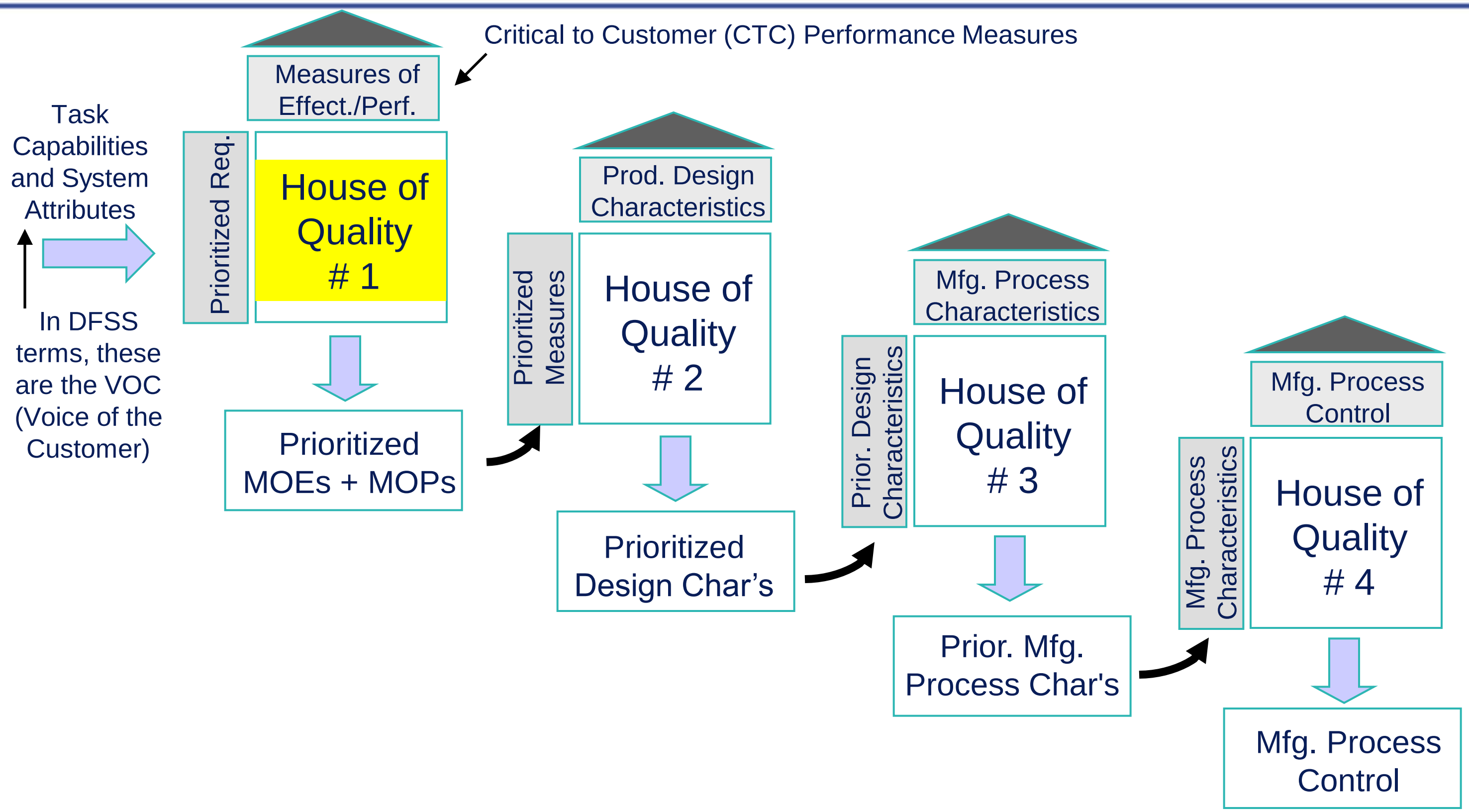
Quality Function Deployment (QFD)



Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability

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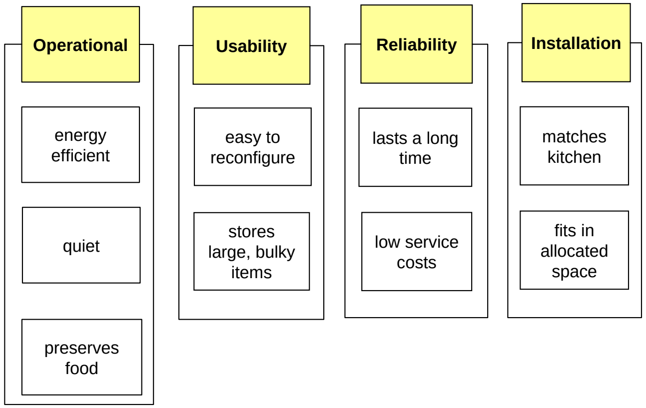
Voice of the Customer (Refrigerator)

VOC

- "Want it to be energy efficient"
- "Want it to be quiet"
- "Needs to preserve food"
- "Want to be able to easily reconfigure the shelves"
- "Want to fit large, bulky items"
- "Should last a long time"
- "Would like it to match my kitchen"
-
-
-

Affinity Diagrams Can Help



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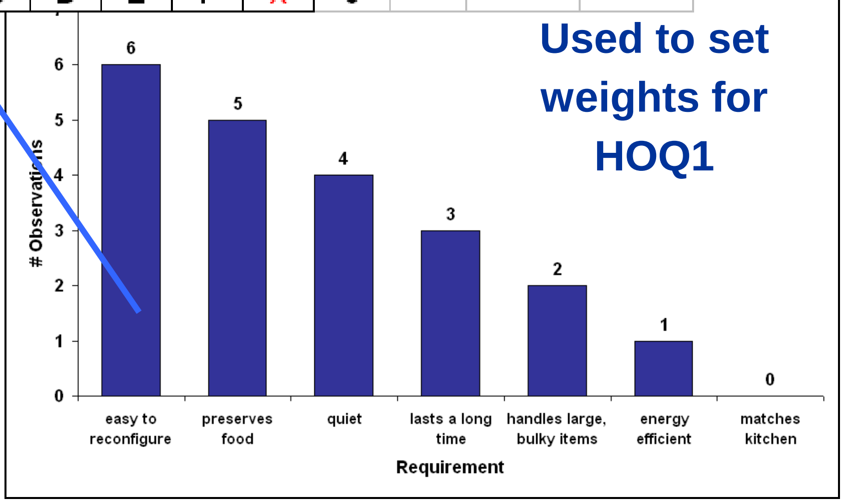
Use Pairwise Comparison to Prioritize

	Customer Requirements	A (energy efficient)	B (quiet)	C (preserves food)	D (easy to reconfigure)	E (handles large, bulky items)	F (lasts a long time)	G (matches kitchen)	Total
A	energy efficient	X	X	X	X	X	X	X	1
B	quiet	B	X	X	X	X	X	X	4
C	preserves food	C	C	X	X	X	X	X	5
D	easy to reconfigure	D	D	D	X	X	X	X	6
E	handles large, bulky items	E	B	C	D	X	X	X	2
F	lasts a long time	F	B	C	D	F	X	X	3
G	matches kitchen	A	B	C	D	E	F	X	0

Example: "Easy to reconfigure" won 6 times.

Used to set weights for HOQ1



Place Customer Requirements & Rating into HOQ #1 (Refrigerator Example)

Grouped customer requirements ↓ | Rating ↓ | Performance Measures

Grouped customer requirements	Rating							
A: energy efficient	2							
B: quiet	4							
C: preserves food	5							
D: easy to reconfigure	5							
E: handles large, bulky items	3							
F: lasts a long time	4							
G: matches kitchen	1							

Rating:

5: Must have for performance
4: Highly desirable feature
3: Desirable feature
2: Usable feature but not critical
1: Nice feature but not critical

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Fill in Performance Measures Across Top

Peformance Measures (CTCs) →		energy efficiency rating	noise level (db)	temperature range	cooling speed (sec. per degree)	% adjustable shelves	disassy / reassy time (sec)	shelf depth and width (in.)	door tray depth (in.)	mean time to failure (hrs)	# available colors
A: energy efficient	2										
B: quiet	4										
C: preserves food	5										
D: easy to reconfigure	5										
E: handles large, bulky items	3										
F: lasts a long time	4										
G: matches kitchen	1										

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Relationships

- Now, determine the strength of the relationships between the customer requirements and the CTCs. Rate the relationship between each customer requirement and each CTC according to the scale below.

9:	Strong Relationship
3:	Medium Relationship
1:	Weak Relationship
Blank:	No Relationship

- Compute a Rank-Ordered Sum for each CTC (multiply strength • rating and add)

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HOQ # 1 …. Prioritizes the Performance Measures

CTCs/FPs
(Functional Domain)

VOC
(Customer Domain)

Customer Requirements:	Importance Rating	energy efficiency rating	noise level (db)	temperature range	cooling speed	% adjustable shelves	disassy / reassy time (sec.)	shelf depth and width (in.)	door tray depth (in.)	mean time to failure	# available colors
A: energy efficient	2	9	1	3	9			1	1	1	
B: quiet	4	3	9	1	3						
C: preserves food	5	3		9	9			1	1	1	
D: easy to reconfigure	5					3	9				
E: handles large, bulky items	3					9	1	9	9		
F: lasts a long time	4	1			1					9	
G: matches kitchen	1										9
Weighted Sums >>>		49	38	55	79	42	48	34	34	43	9

Task Capabilities and System Attributes are mapped to Performance Measures

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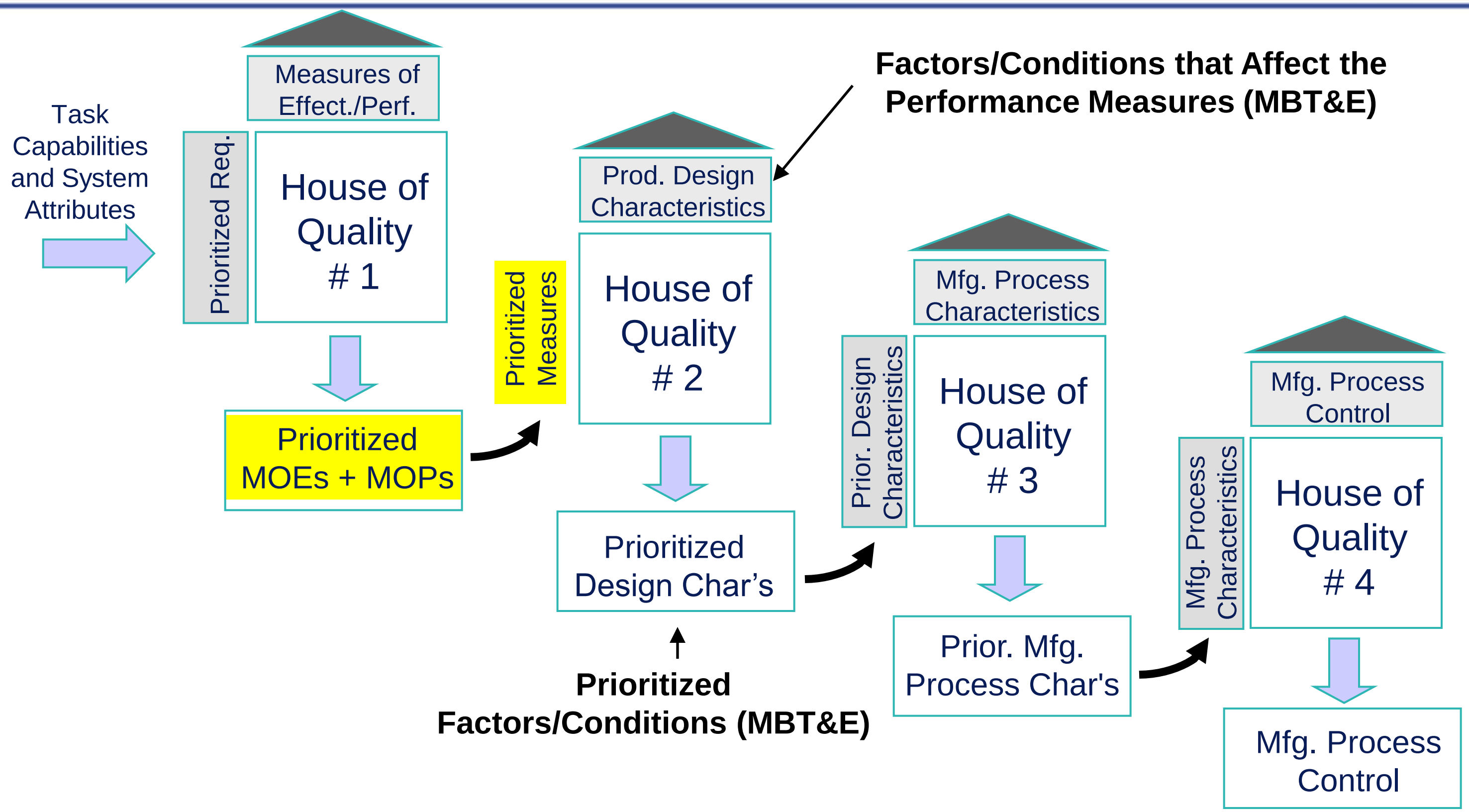
Prioritized Measures Become Side of HOQ # 2



Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability

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Case Study: OnTech Self-Heating Container

Identify

Key Features (VOC)

- Self-heating
- Activated by button on bottom of can
- Used for hot beverages and soups
- Disposable
- Environmentally compatible

Affinitization of Consumer Appeal

Identify

Customer Appeal

CONCEPT

(Packaging)

- **"Portable"**
- **"Self Heating"**
- **"Easy to Use"**
- **"Unique"**

PRODUCT

(Taste)

- **"Not bitter"**
- **"Fresh"**
- **"Smooth"**
- **"Varieties"**

Simply...

I want to be able to buy one cup with a button on it, press the button, and it gets hot, and tastes great, then I can throw it away when I'm done.

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Pairwise Comparison

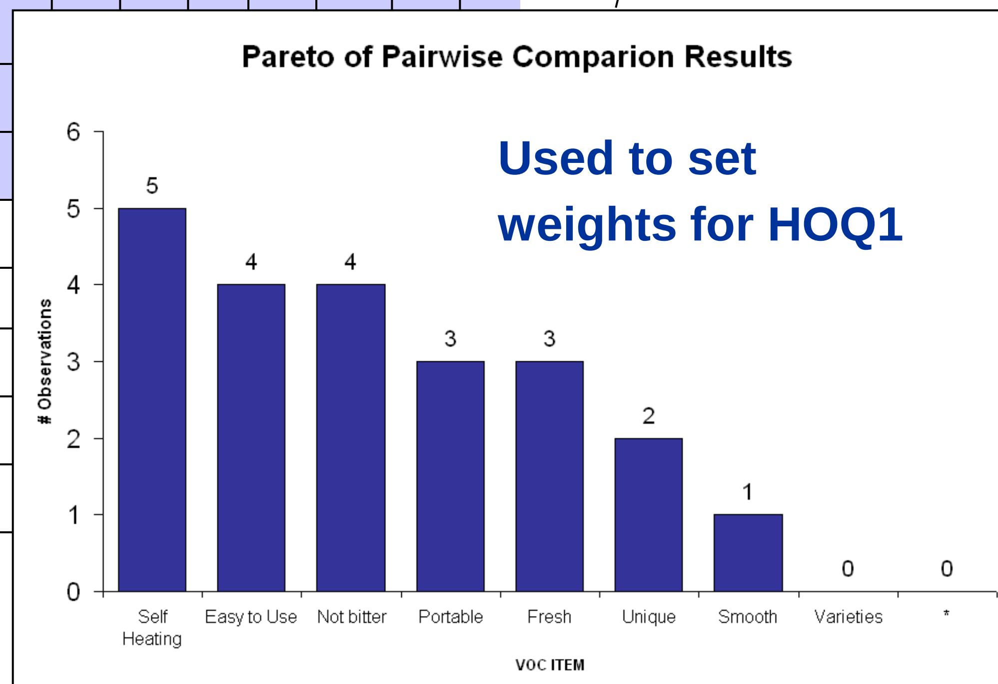
A B C D E F G H . .

Identify

VOC Prioritization

		Portable	Self Heating	Easy to Use	Unique	Not bitter	Fresh	Smooth	Varieties	.	.	.
A	Portable											
B	Self Heating	A										
C	Easy to Use	A	B									
D	Unique	A	B									
E	Not bitter	.										
F	Fresh	.										
G	Smooth	.										
H	Varieties											
.	.											
.	.											
	.											

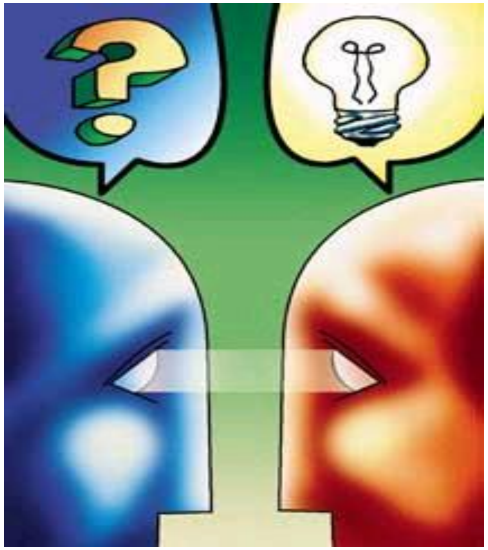
<u>Example:</u>
"Self-Heating" won 5 times.



VOC ➡ CTCs

Identify

Customer Domain Language to
Functional Domain Language



1st HOQ and Functional Domain

Identify

CTCs/Perf.Measures
(Functional Domain)

VOC
(Customer Domain)

	wt	Dimensionality/Shape	Beverage Temperature	Time (sec) to use	Can Temperature	Weight	Taste	..	
Portable	3	9	3	9	3	3			
Self Heating	5	3	9	9	9	3			
Easy to Use	4	3	1		3	3			
Unique	2								
.									
.									
.									
Prioritized CTCs		54	58	72	66	36	.	.	

Voice of the Customer is mapped to Functional or Performance Measures

Scores are multiplied by weights and summed below

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The Design Phase

The DFSS Process: Identify, Design, Optimize, Validate

- The **Identify** Phase
  - The DFSS Scorecard
  - Voice of the Customer (VOC)

- ***The Design Phase***
  - ***Translating the VOC (Requirements Flowdown)***
  - ***Concept Generation and Selection***
  - ***Transfer Functions***
  - ***Critical Parameter Management***

- The **Optimize** Phase
  - Multiple Response Optimization
  - Expected Value Analysis Using Monte Carlo Simulation
  - Parameter Design
  - Tolerance Allocation

- The **Validate** Phase
  - High Throughput Testing

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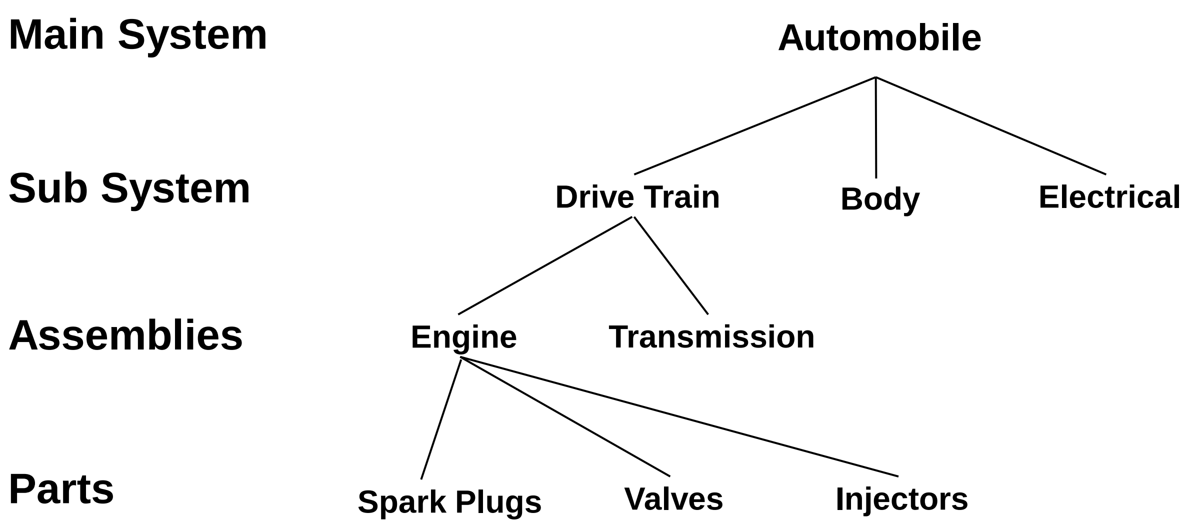
Systems Engineering



- **Complex products may require the "Divide and Conquer" approach.**
- **Requirements are flowed down, while capabilities are rolled up.**
- **System Engineers are the masters of the scorecard and make tradeoff decisions.**

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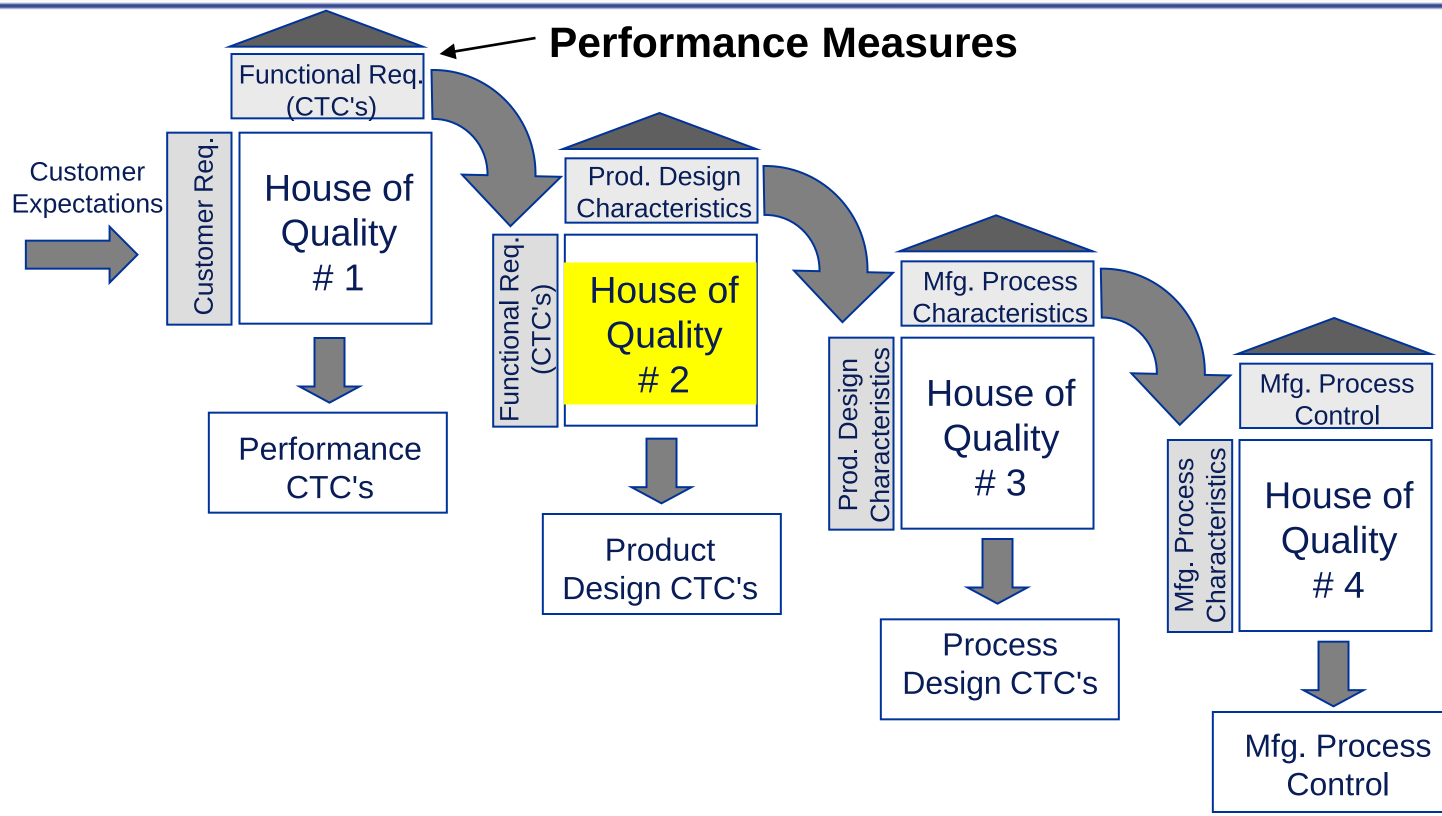
Requirements Flowdown Using QFD



Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability

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Formulate Design Concepts

- Create alternative designs that fulfill CTC's.
- Compare designs with functional requirements (CTC's)
- Choose the best design
  - How do we decide which is the best approach?
- Assess risk of chosen design.
- Tools for Concept Generation and Selection
  - Axiomatic Design
  - TRIZ
  - Pugh Concept Selection

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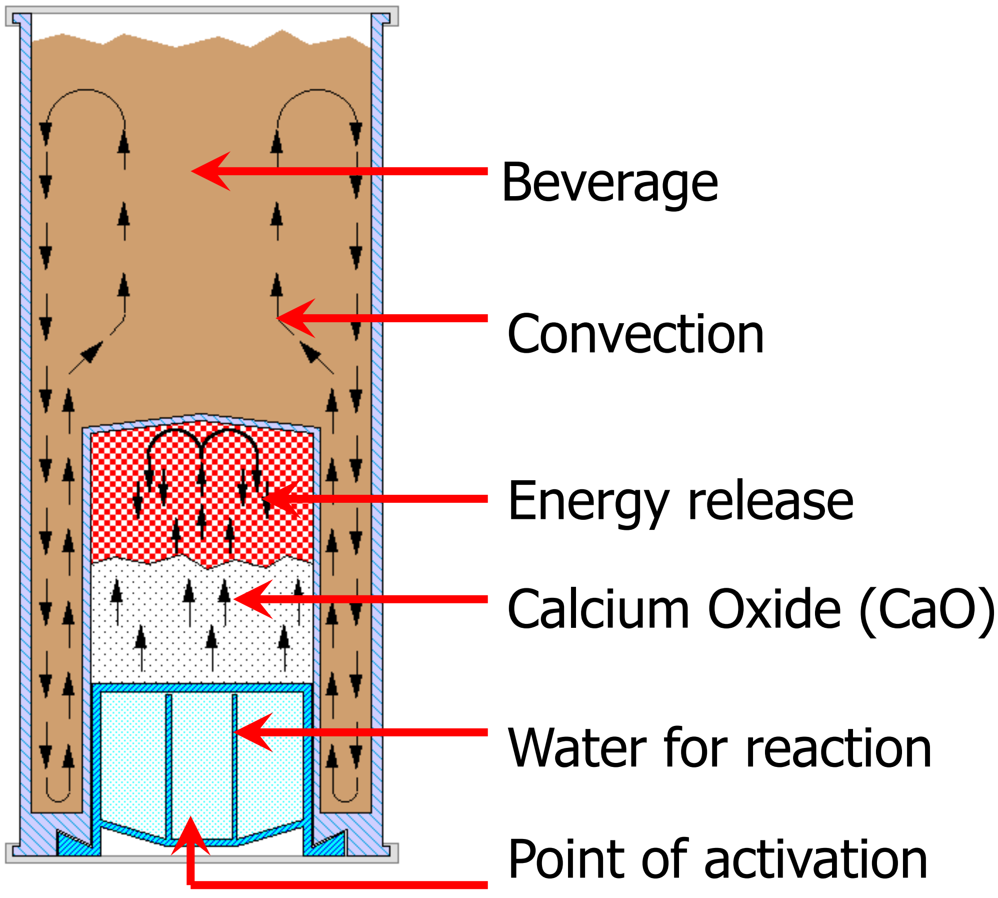
Case Study: General Design Concept

Design



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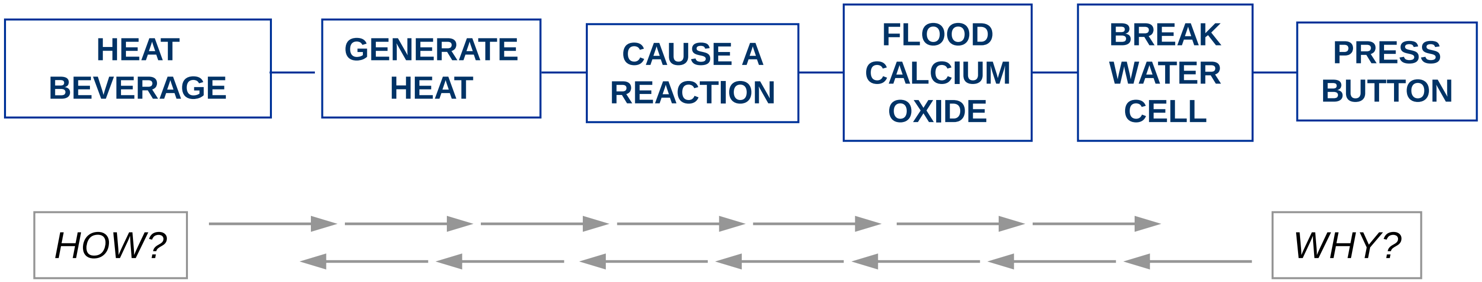
FAST (Functional Analysis System Technique)

Design

FAST allows us to quickly design the key functionality of the product (system).



All of the "hows" and "whys" must be answered (both directions).

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2nd HOQ: Functional → Physical Domain

DPs
(Physical Domain)

CTCs (FPs)
(Functional Domain)

Design

CTCs (FPs)	wt	Wall thickness	CaO mass	H_20 volume	Button force to activate	.	.	
Can Temp	4	9	3	1				
Time to Use	5	3	9	9				
Dimensionality	3	1	3	3				
Beverage Temp	3	1	3					
.								
.								
Prioritized DPs		57	75	67	.	.	.	

Functional Parameters are mapped to Design Parameters

Scores are multiplied by weights and summed below

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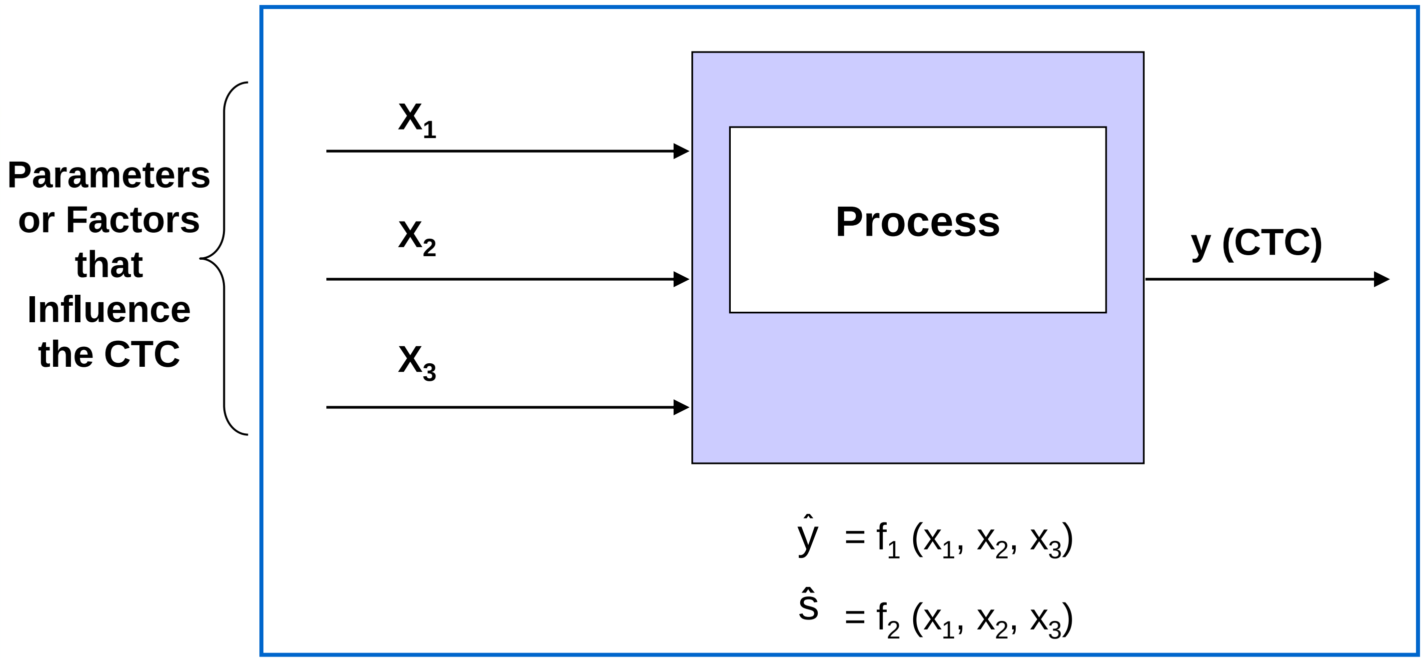
Transfer Function: The Bridge to Innovation

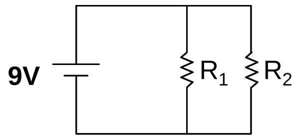


Where does the transfer function come from?

- **Exact transfer function**
- **Approximations**
  - **DOE**
  - **Historical Data Analysis**
  - **Simulation**

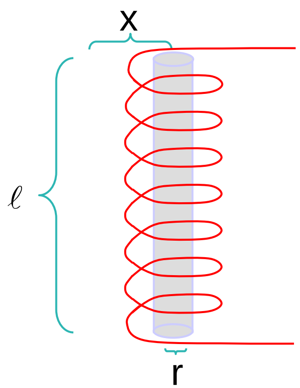
Exact Transfer Functions

- Engineering Relationships
  - $V = IR$
  - $F = ma$



The equation for current (I) through this DC circuit is defined by:

$$I = \frac{V}{\frac{R_1 \cdot R_2}{R_1 + R_2}} = \frac{V(R_1 + R_2)}{R_1 \cdot R_2}$$



The equation for magnetic force at a distance X from the center of a solenoid is:

$$H = \frac{NI}{2\ell}\left[\frac{.5\ell + x}{\sqrt{r^2 + (.5\ell + x)^2}} + \frac{.5\ell - x}{\sqrt{r^2 + (.5\ell - x)^2}}\right]$$

Where
- N: total number of turns of wire in the solenoid
- I : current in the wire, in amperes
- r : radius of helix (solenoid), in cm
- ℓ : length of the helix (solenoid), in cm
- x : distance from center of helix (solenoid), in cm
- H : magnetizing force, in amperes per centimeter

Hierarchical Transfer Functions

$$Y = \text{Gross Margin} = \frac{\text{Gross Profit}}{\text{Gross Revenue}}$$

$$Y = f(y_1, y_2, y_3, y_4, y_5, y_6)$$

$$= \frac{(\overset{y_1}{Rev_{equip}} - \overset{y_2}{COG}) + (\overset{y_3}{Rev_{post\ sales}} - \overset{y_4}{Cost_{post\ sales}}) + (\overset{y_5}{Rev_{fin}} - \overset{y_6}{Cost_{fin}})}{y_1 + y_3 + y_5}$$

$$\overset{y_4}{Cost_{post\ sales}} = f(\overset{x_1}{\text{field cost}}, \overset{x_2}{\text{remote services}}, \overset{x_3}{\text{suppliers}})$$

$$x_1 = f(\text{direct labor, freight, parts, depreciation})$$

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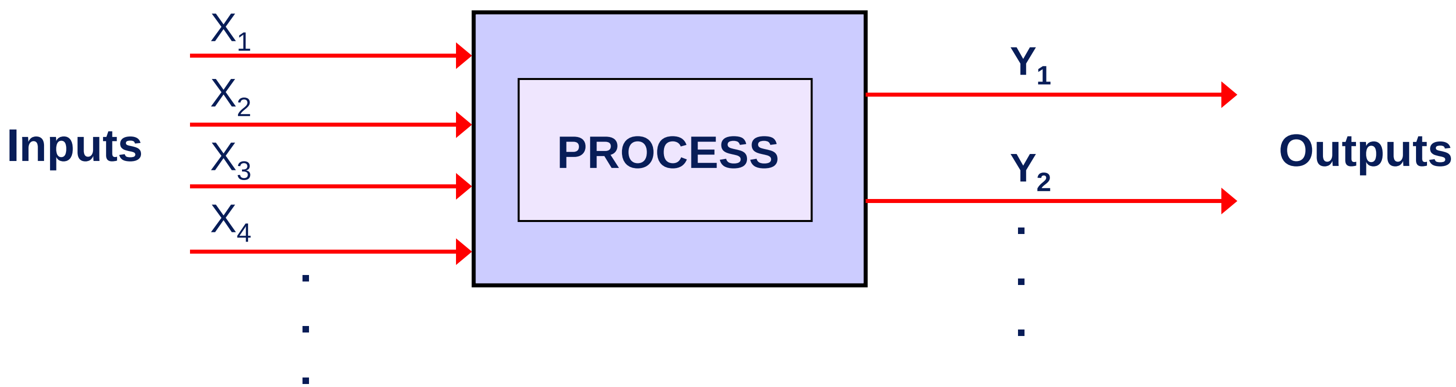
What is a Designed Experiment?

Purposeful changes of the inputs (factors) in order to observe corresponding changes in the output (response).



Run	X_1	X_2	X_3	X_4	Y_1	Y_2	. . . . . .	$\bar{Y}$	S_Y
1									
2									
3									
.									
.									

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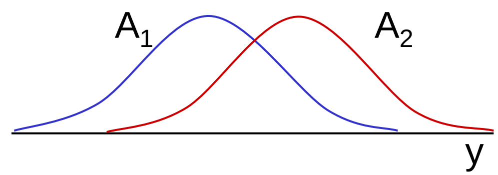
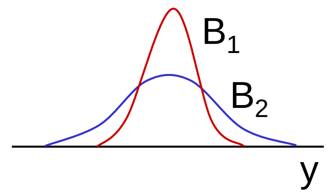
DOE Helps Determine How Inputs Affect Outputs

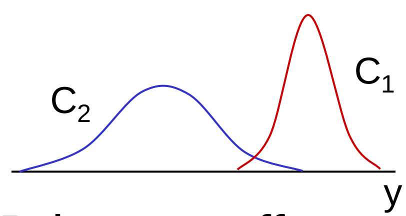
i) Factor A affects the average of y



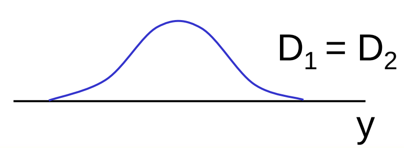
ii) Factor B affects the standard deviation of y



iii) Factor C affects the average and the standard deviation of y



iv) Factor D has no effect on y



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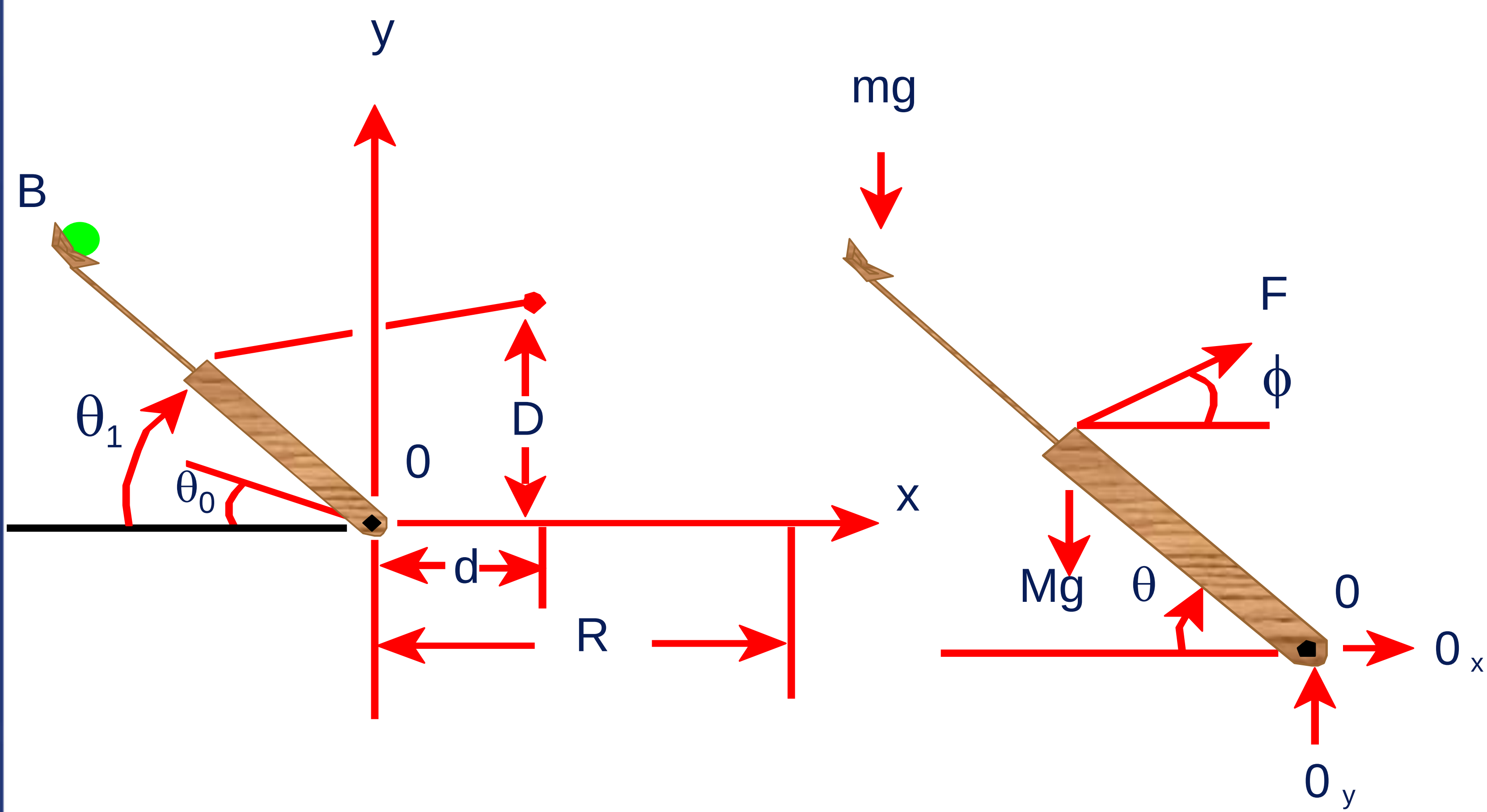
Catapulting Power into DFSS

Statapult ® Catapult

The Theoretical Approach



The Theoretical Approach (cont.)

$$I_0\ddot{\theta} = r_F F(\theta)\sin\theta\cos\varphi - (Mgr_G + mgr_B)\sin\theta \qquad \tan\phi = \frac{D - r_F\sin\theta}{d + r_F\cos\theta},$$

$$\frac{1}{2}I_0\dot{\theta}^2 = r_F\int_{\theta_0}^{\theta} F(\theta)\sin\theta\cos\varphi\, d\theta - (Mgr_G + mgr_B)(\sin\theta - \sin\theta_0)$$

$$\frac{1}{2}I_0\dot{\theta}_1^2 = r_F\int_{\theta_0}^{\theta_1} F(\theta)\sin\theta\cos\varphi\, d\theta - (Mgr_G + mgr_B)(\sin\theta_1 - \sin\theta_0).$$

$$x = v_B\cos\left(\frac{\pi}{2} - \theta_1\right)t - \frac{1}{2}r_B\cos\theta_1 \qquad y = r_B\sin\theta_1 + v_B\sin\left(\frac{\pi}{2} - \theta_1\right)t - \frac{1}{2}gt^2.$$

$$r_B\sin\theta_1 + (R + r_B\cos\theta_1)\tan\left(\frac{\pi}{2} - \theta_1\right) - \frac{g}{2V_B^2}\frac{(R + r_B\cos\theta_1)^2}{\cos^2\left(\frac{\pi}{2} - \theta_1\right)} = 0.$$

$$\frac{gI_0}{4r_B}\frac{(R + r_B\cos\theta_1)^2}{\cos^2\left(\frac{\pi}{2} - \theta_1\right)\left[r_B\sin\theta_1 + (R + r_B\cos\theta_1)\tan\left(\frac{\pi}{2} - \theta_1\right)\right]}$$

$$= r_F\int_{\theta_0}^{\theta_1} F(\theta)\sin\theta\cos\phi\, d\theta - (Mgr_G + mgr_B)(\sin\theta_1 - \sin\theta_0).$$

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Statapult® DOE Demo
(The Empirical Approach)

	Actual Factors		Coded Factors			Response Values			
Run	A	B	A	B	AB	Y_1	Y_2	$\bar{Y}$	S
1	144	2	-1	-1	+1				
2	144	3	-1	+1	-1				
3	160	2	+1	-1	-1				
4	160	3	+1	+1	+1				

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What Makes DOE so Powerful?
(Orthogonality: both vertical and horizontal balance)

A Full Factorial Design for 3 Factors A, B, and C, Each at 2 levels:

Run	A	B	C	AB	AC	BC	ABC
1	-	-	-	+	+	+	-
2	-	-	+	+	-	-	+
3	-	+	-	-	+	-	+
4	-	+	+	-	-	+	-
5	+	-	-	-	-	+	+
6	+	-	+	-	+	-	-
7	+	+	-	+	-	-	-
8	+	+	+	+	+	+	+

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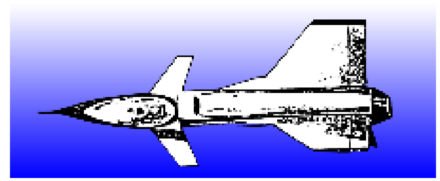
Value Delivery: Reducing Time to Market for New Technologies



INPUT | **OUTPUT**

Pitch <)	(0, 15, 30)
Roll <)	(0, 15, 30)
W1F <)	(-15, 0, 15)
W2F <)	(-15, 0, 15)
W3F <)	(-15, 0, 15)

→ **Modeling Flight Characteristics of New 3-Wing Aircraft** → Six Aero-Characteristics

- Total # of Combinations $= 3^5 = 243$
- Central Composite Design: n = 30

Patent Holder: Dr. Bert Silich

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Aircraft Equations

C_L = .233 + .008(P)^2 + .255(P) + .012(R) - .043(WD1) - .117(WD2) + .185(WD3) + .010(P)(WD3) - .042(R)(WD1) + .035(R)(WD2) + .016(R)(WD3) + .010(P)(R) - .003(WD1)(WD2) - .006(WD1)(WD3)

C_D = .058 + .016(P)^2 + .028(P) - .004(WD1) - .013(WD2) + .013(WD3) + .002(P)(R) - .004(P)(WD1) - .009(P)(WD2) + .016(P)(WD3) - .004(R)(WD1) + .003(R)(WD2) + .020(WD1)^2 + .017(WD2)^2 + .021(WD3)^2

C_Y = -.006(P) - .006(R) + .169(WD1) - .121(WD2) - .063(WD3) - .004(P)(R) + .008(P)(WD1) - .006(P)(WD2) - .008(P)(WD3) - .012(R)(WD1) - .029(R)(WD2) + .048(R)(WD3) - .008(WD1)^2

C_M = .023 - .008(P)^2 + .004(P) - .007(R) + .024(WD1) + .066(WD2) - .099(WD3) - .006(P)(R) + .002(P)(WD2) - .005(P)(WD3) + .023(R)(WD1) - .019(R)(WD2) - .007(R)(WD3) + .007(WD1)^2 - .008(WD2)^2 + .002(WD1)(WD2) + .002(WD1)(WD3)

C_{YM}= .001(P) + .001(R) - .050(WD1) + .029(WD2) + .012(WD3) + .001(P)(R) - .005(P)(WD1) - .004(P)(WD2) - .004(P)(WD3) + .003(R)(WD1) + .008(R)(WD2) - .013(R)(WD3) + .004(WD1)^2 + .003(WD2)^2 - .005(WD3)^2

C_e = .003(P) + .035(WD1) + .048(WD2) + .051(WD3) - .003(R)(WD3) + .003(P)(R) - .005(P)(WD1) + .005(P)(WD2) + .006(P)(WD3) + .002(R)(WD1)

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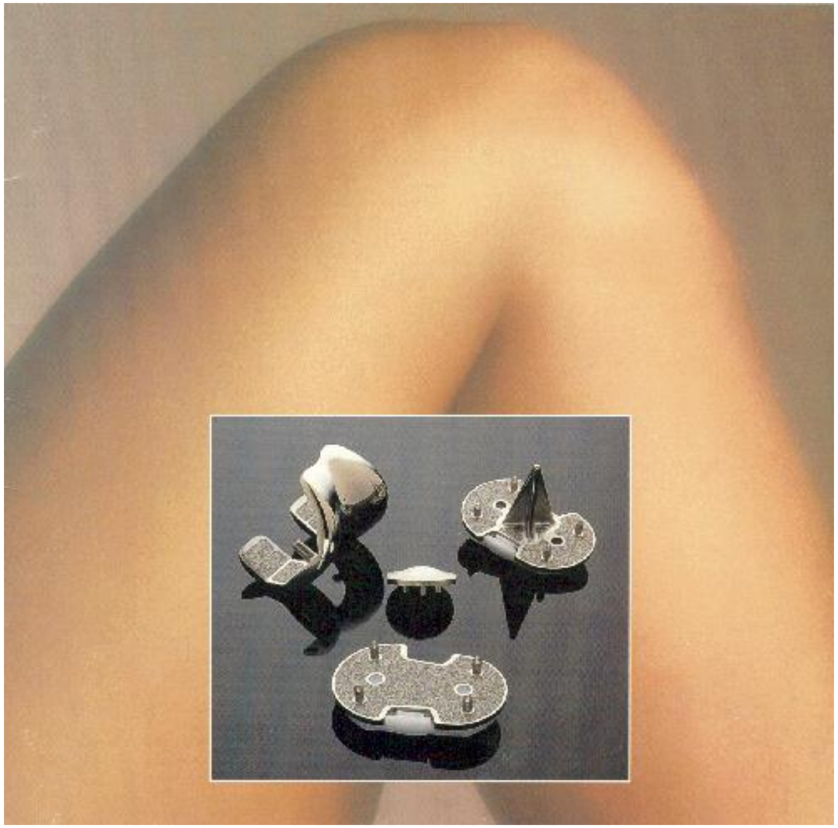
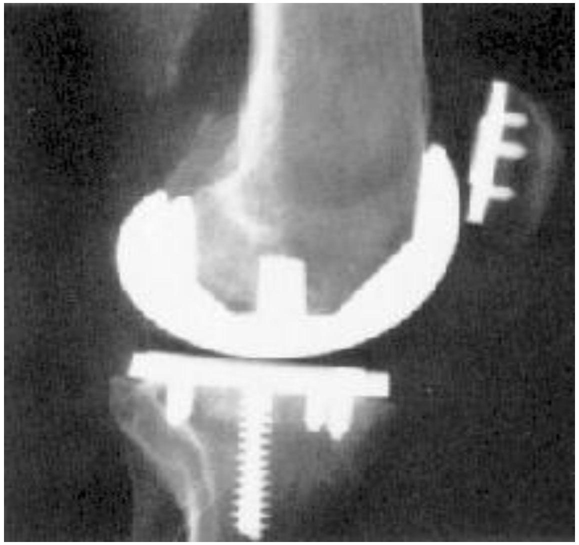
Fusing Titanium and Cobalt-Chrome





Courtesy Rai Chowdhary

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DOE "Market Research" Example

Suppose that, in the auto industry, we would like to investigate the following automobile attributes (i.e., factors), along with accompanying levels of those attributes:

A: Brand of Auto:	-1 = foreign		+1 = domestic
B: Auto Color:	-1 = light	0 = bright	+1 = dark
C: Body Style:	-1 = 2-door	0 = 4-door	+1 = sliding door/hatchback
D: Drive Mechanism:	-1 = rear wheel	0 = front wheel	+1 = 4-wheel
E: Engine Size:	-1 = 4-cylinder	0 = 6-cylinder	+1 = 8-cylinder
F: Interior Size:	-1 ≤ 2 people	0 = 3-5 people	+1 ≥ 6 people
G: Gas Mileage:	-1 ≤ 20 mpg	0 = 20-30 mpg	+1 ≥ 30 mpg
H: Price:	-1 ≤ $20K	0 = $20-$40K	+1 ≥ $40K

In addition, suppose the respondents chosen to provide their preferences to product profiles are taken based on the following demographic:

J: Age:	-1 ≤ 25 years old	+1 ≥ 35 years old
K: Income:	-1 ≤ $30K	+1 ≥ $40K
L: Education:	-1 < BS	+1 ≥ BS

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DOE "Market Research" Example (cont.)

Question: Choose the best design for evaluating this scenario

Answer: L_{18} design with attributes A - H in the inner array and factors J, K, and L in the outer array, resembling an L_{18} robust design, as shown below:

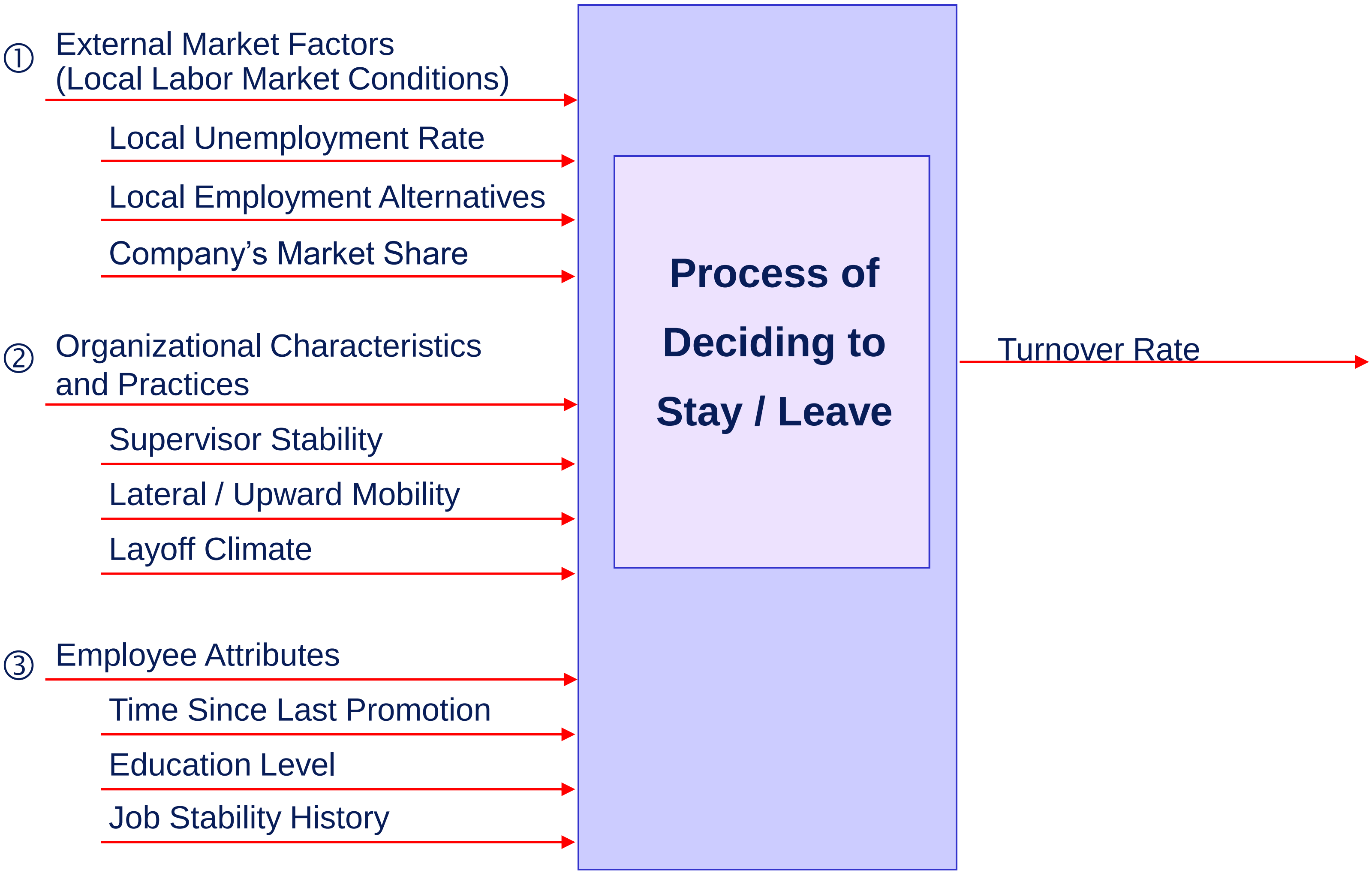
Run*	A	B	C	D	E	F	G	H		y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	$\bar{y}$	s
									L	-	+	-	+	-	+	-	+		
									K	-	-	+	+	-	-	+	+		
									J	-	-	-	-	+	+	+	+		
1	-	-	-	-	-	-	-	-											
2	-	-	0	0	0	0	0	0											
3	-	-	+	+	+	+	+	+											
4	-	0	-	-	0	0	+	+											
5	-	0	0	0	+	+	-	-											
6	-	0	+	+	-	-	0	0											
7	-	+	-	0	-	+	0	+											
8	-	+	0	+	0	-	+	-											
9	-	+	+	-	+	0	-	0											
10	+	-	-	+	+	0	0	-											
11	+	-	0	-	-	+	+	0											
12	+	-	+	0	0	-	-	+											
13	+	0	-	0	+	-	+	0											
14	+	0	0	+	-	0	-	+											
15	+	0	+	-	0	+	0	-											
16	+	+	-	+	0	+	-	0											
17	+	+	0	-	+	-	0	+											
18	+	+	+	0	-	0	+	-											

Segmentation of the population or

Respondent Profiles

* 18 different product profiles

Modeling The Drivers of Turnover*



*Adapted from Harvard Business Review article on Boston Fleet Bank, April 2004, pp 116-125

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The Value of Transfer Functions

- Provide a simple and compact way of understanding relationships between performance measures or response variables (y's) and the factors (x's) that influence them.
- Allow for the prediction of the response variable (y), with associated risk levels, before any change in the product or process is made.
- Allow for the assessment of process or product capability in the presence of uncontrolled variation or noise.
- Allow the very quick manipulation of complex systems using Monte Carlo Simulation (i.e., Expected Value Analysis) for the purpose of assessing risk.
- Provide a very easy way to optimize performance via robust or parameter design and tolerance allocation.
- Make sensitivity analysis easy and straightforward.
- Greatly enhance one's knowledge of a product or process.
- In general, they are the gateway to systematic innovation.
- Provide a meaningful metric for the maturity in DFSS for any organization.

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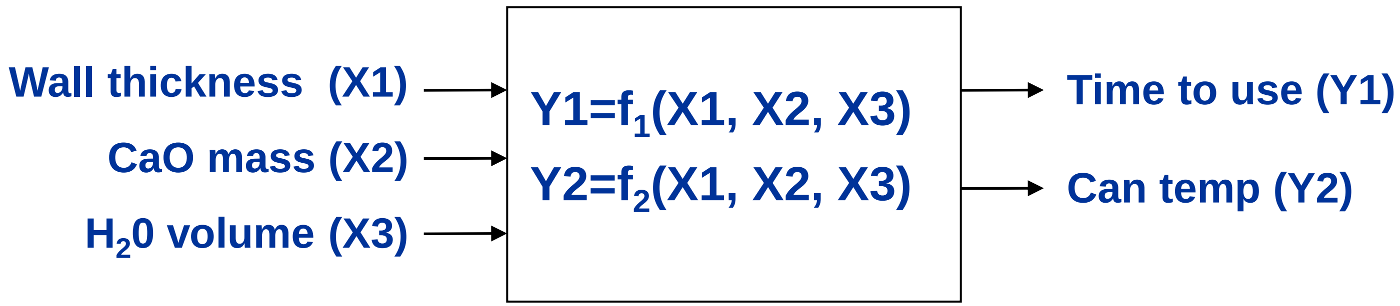
Case Study: Transfer Functions

Design

Example: "Time to use" and "Can temp" as a function of "Wall thickness", "CaO mass", and "H_2O volume"



How do we find the functions f_1 and f_2?

- First principle equations (Physics / Engineering equations)
- Analytical Models (Simulation and Regression) FEA, CFD, etc.
- Empirical models (Design of Experiments)

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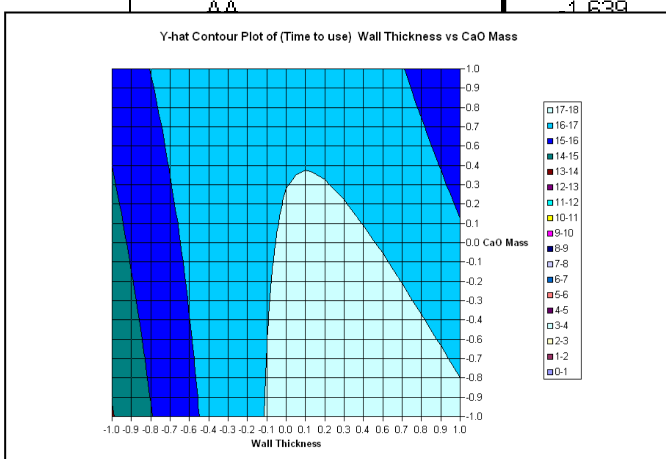
Empirical Modeling via DOE

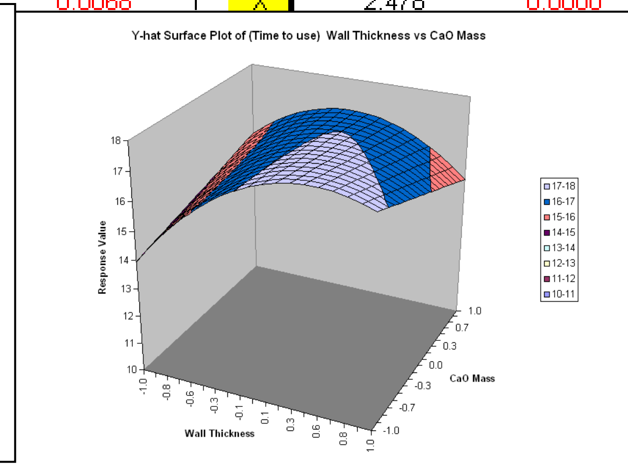
Design

Factor	A	B	C		Time to use				
Row #	Wall Thick	CaO Mass	H2O Volume		Y1	Y2	Y3	Y4	Y5
1	-1	-1	-1		15.41278	16.572	15.81977	10.29423	10.92083
2	-1	-1	1		15.16945	16.6466	14.76726	9.096769	12.39497
3	-1	1	-1		13.12958	16.93513	17.3345	13.11604	11.0545
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									

Factor	A	B	C		Max can temp				
Row #	Wall Thick	CaO Mass	H2O Volume		Y1	Y2	Y3	Y4	Y5
1	-1	-1	-1		108.1381	103.948	107.5071	102.9392	104.3727
2	-1	-1	1		109.8235	105.5967	108.1956	109.2639	104.0185
3	-1	1	-1		108.0081	109.2598	110.8279	109.7068	109.4276

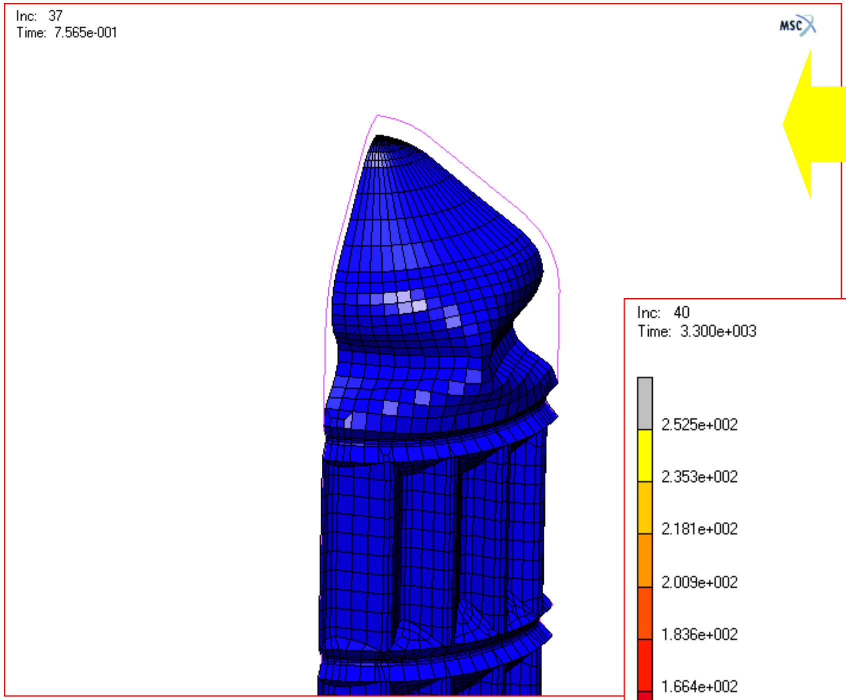
Y-hat Model		Time to use				Max can temp			
Factor	Name	Coeff	P(2 Tail)	Tol	Active	Coeff	P(2 Tail)	Tol	Active
Const		17.055	0.0000			106.91	0.0000		
A	Wall Thickness	0.73753	0.0444	1	X	0.71745	0.0302	1	X
B	CaO Mass	-0.17772	0.6237	1	X	0.56822	0.0842	1	X
C	H2O Volume					0.49940	0.1282	1	X
AB		-0.91022	0.0269	1	X	-1.564	0.0001	1	X
AC						-1.128	0.0027	1	X
AA		-1.639	0.0068	1	X	2.478	0.0000	1	X





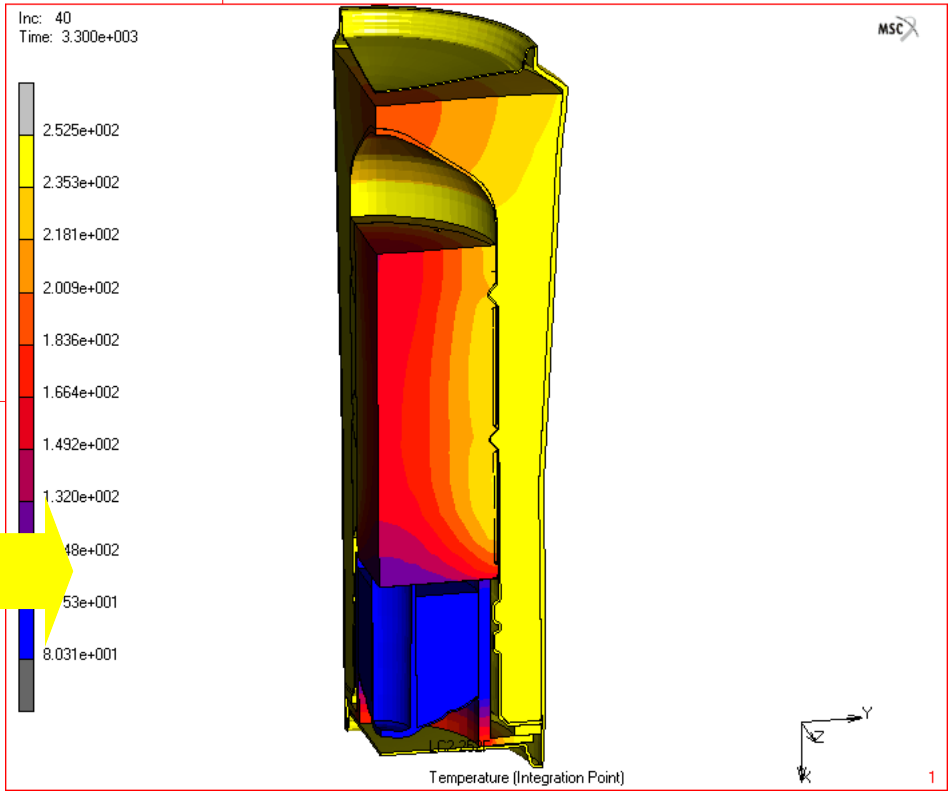
Analytical Modeling via FEA/CFD

Design



Finite Element Analysis (FEA) for modeling structural components

Computational Fluid Dynamics (CFD) for modeling temperature (fluid) components



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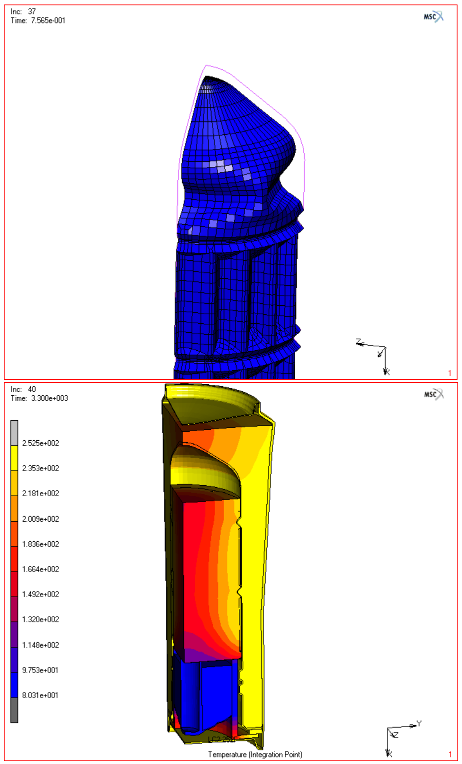
Analytical Modeling with Regression

Design

FEA / CFD Model



Regression Modeling

Y-hat Model

Factor	Name	Response #1 Coeff	P(2 Tail)	Tol	Active	Response #2 Coeff	P(2 Tail)	Tol	Active	Response #3 Coeff	P(2 Tail)	Tol	Active
Const		-0.45862	0.9726			10.817	0.3815			-8.245	0.4975		
A													
B													
C													
AB													
AC													
BC													
ABC													
AA													
BB													
CC													
	Total	290055.5	79			271616.0	79			241854.9	79		

Factor	A	B	C	Response #1				
Row #	A	B	C	Y1	Y2	Y3	Y4	Y5
1	-1	-1	-1	-12	-79	4	-1	18
2	-1	-1	1	-63	87	6	83	-63
3	-1	1	-1	-47	57	32	38	68
4	-1	1	1	-81	74	70	-54	11
5	1	-1	-1	71	-89	-31	-50	79
6	1	-1	1	62	49	-37	-68	74
7	1	1	-1	-55	-67	95	25	31
8	1	1	1	-94	-62	54	-95	43
9	0	0	0	96	-66	65	22	41
10	0	0	0	-100	11	95	-65	-70
11	-1	0	0	25	-16	-83	74	-23
12	1	0	0	45	44	23	-8	58
13	0	-1	0	78	-50	-31	91	-69
14	0	1	0	-18	-54	-3	-43	-75
15	0	0	-1	-90	-30	85	48	73
16	0	0	1	-53	18	-94	-26	61

Prediction

Factor	Name	Low	High	Exper
A	Wall Thickness	-1	1	-1
B	CaO Mass	-1	1	-1
C	H2O Volume	-1	1	-0.943791176

Multiple Response Prediction

	Y-hat	S-hat	99% Confidence Interval Lower Bound	99% Confidence Interval Upper Bound
Time to use	13.9460	0.6050	12.131	15.761
Max can temp	105.0000	1.1425	101.573	108.428

Predicted results validated in model

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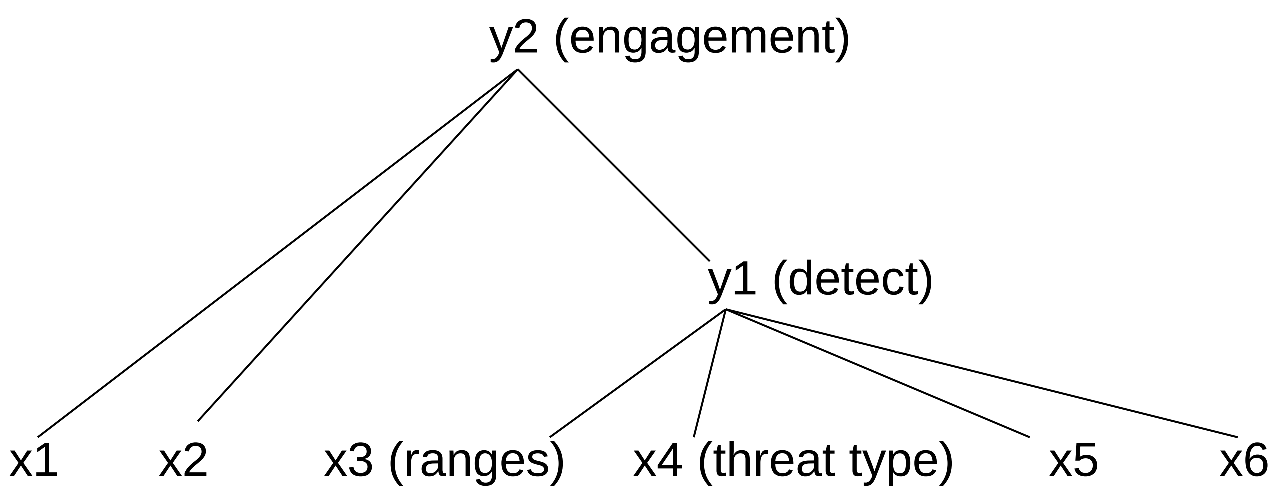
Critical Parameter Management and COIs

– A Critical Operational Issue (COI) is linked to operational effectiveness and suitability.

– It is typically phrased as a question, e.g.,

Will the system ***detect*** the ***threat*** in a ***combat environment*** at adequate ***range*** to allow for successful ***engagement***?



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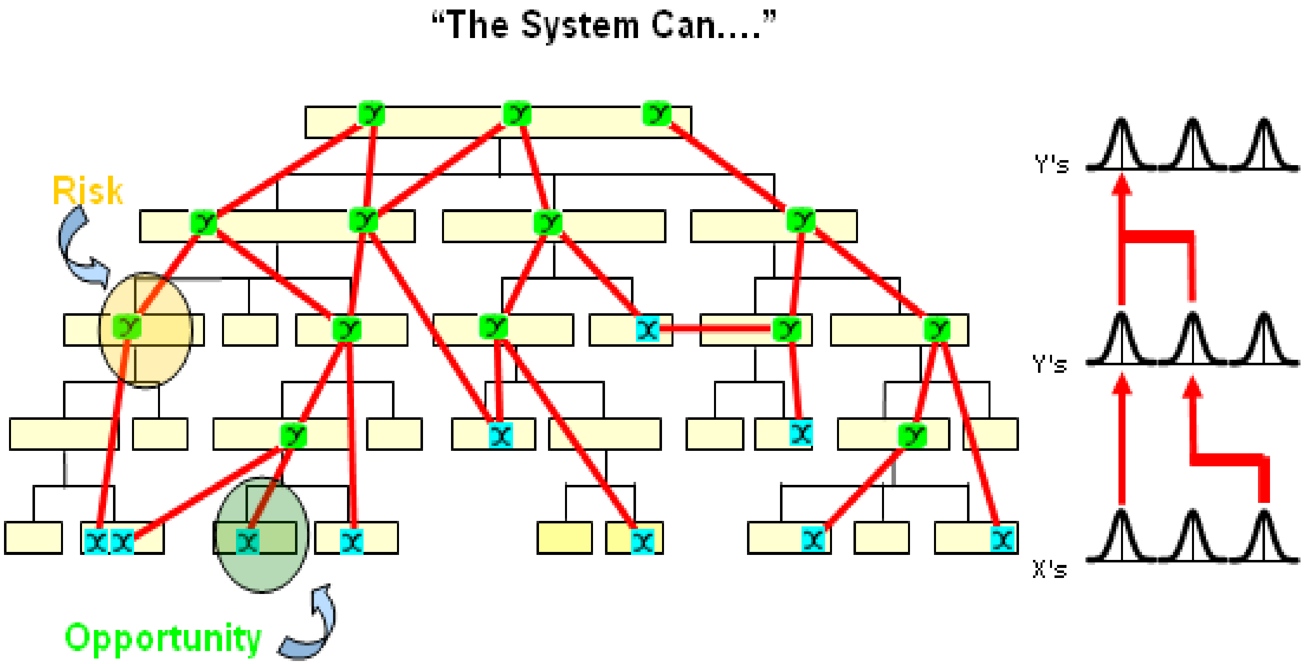
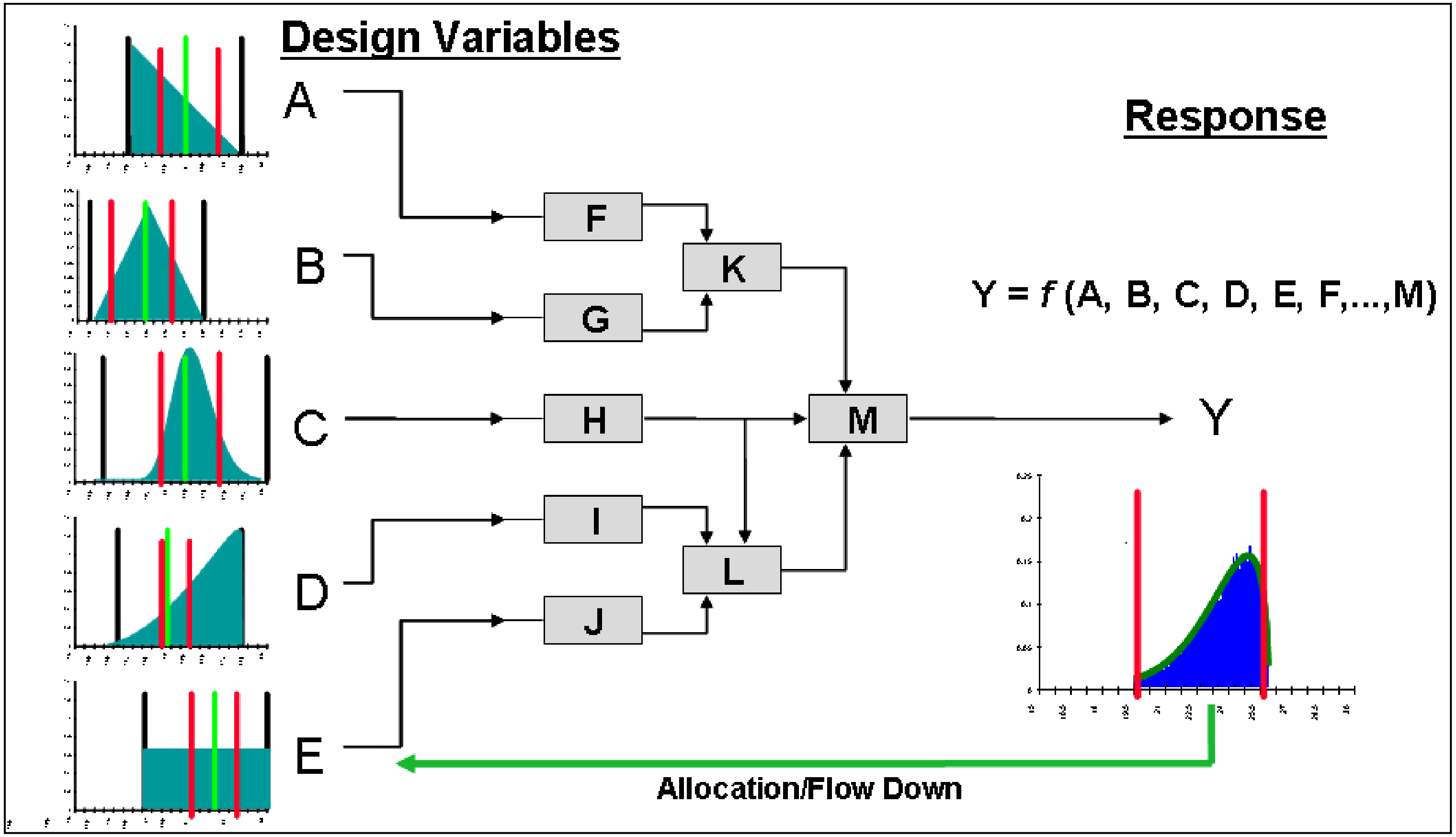
DOE Enables Critical Parameter Management (CPM)

CPM is a systems engineering best practice that is extremely useful in managing, analyzing, and reporting technical product performance. It is also very useful in decomposing COIs and developing linkages between measures and task capabilities/system attributes.



DOE Enables the Composition of Functions



The Optimize Phase

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The DFSS Process: Identify, Design, Optimize, Validate

– The **Identify** Phase
  –The DFSS Scorecard
  –Voice of the Customer (VOC)
– The **Design** Phase
  –Translating the VOC (Requirements Flowdown)
  –Concept Generation and Selection
  –Transfer Functions
  –Critical Parameter Management

–The Optimize Phase
  –Multiple Response Optimization
  –Expected Value Analysis (Monte Carlo Simulation)
  –Parameter (Robust) Design
  –Tolerance Allocation

– The **Validate** Phase
  –High Throughput Testing

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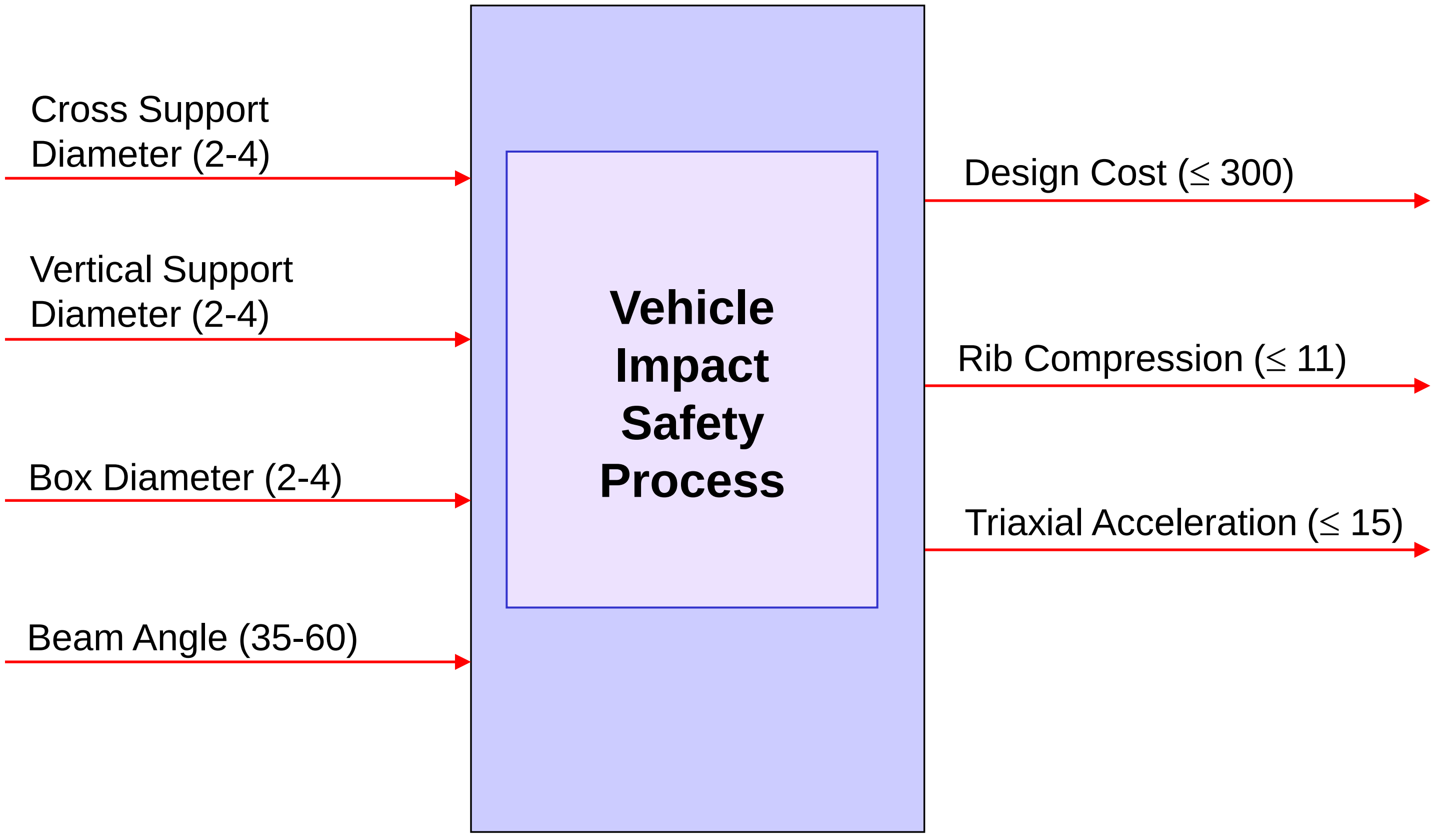
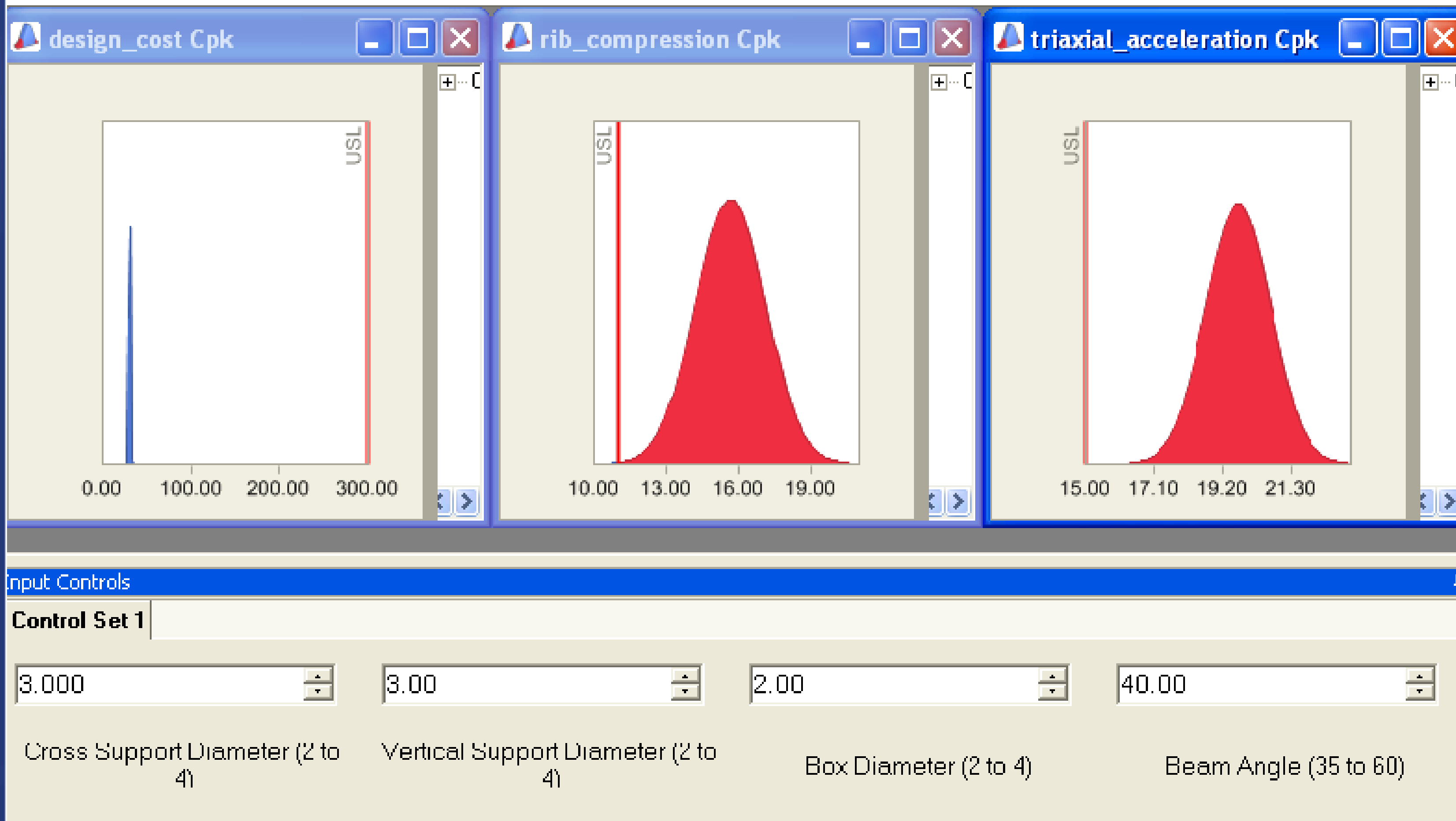
Multiple Response Optimization Simulation* Example



* From **SimWare Pro** by Philip Mayfield and Digital Computations

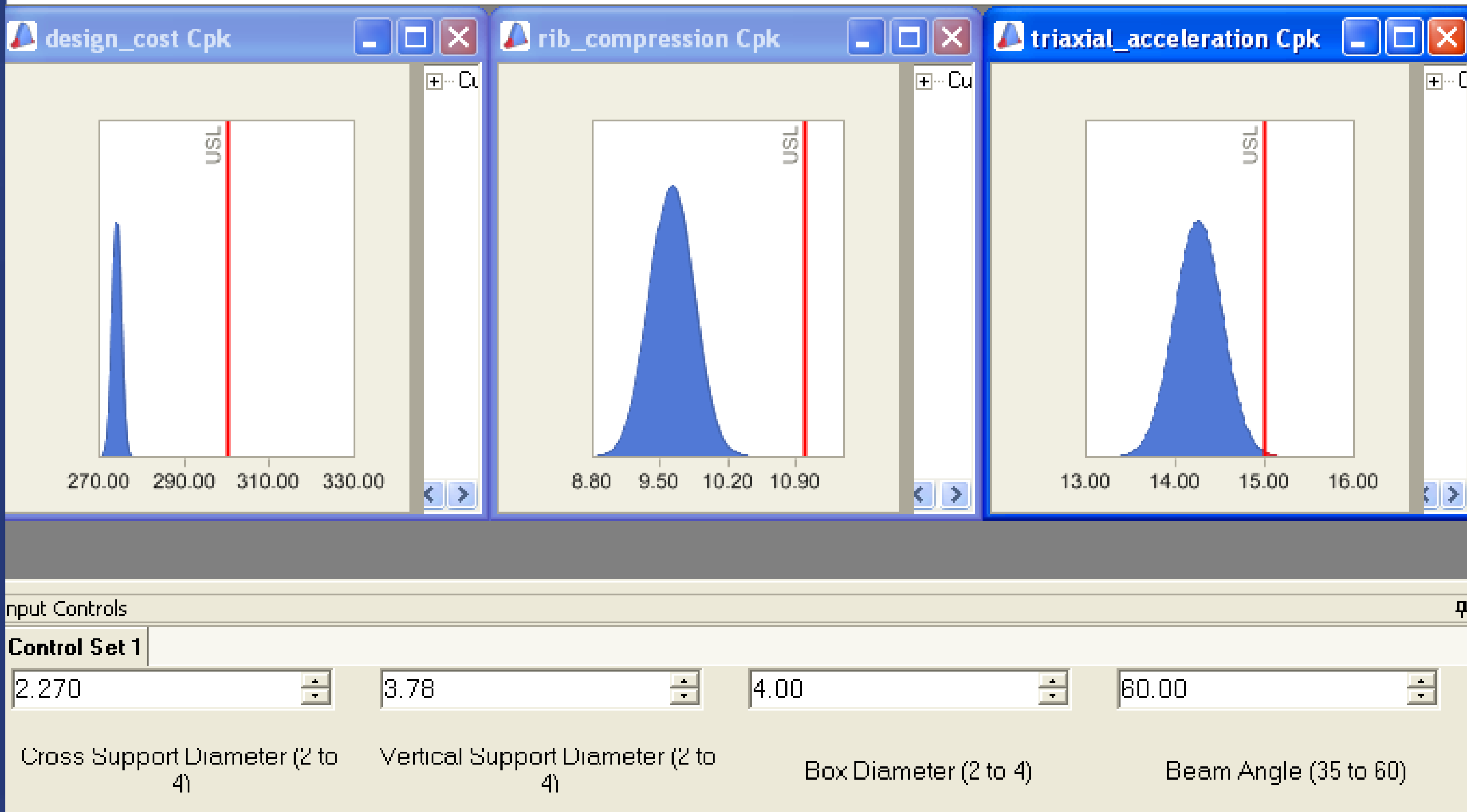
Multiple Response Optimization (cont.)

Capability Prior to Optimization



Multiple Response Optimization (cont.)

Capability After Optimization



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DFSS with Monte Carlo Simulation

- **Expected Value Analysis**
- **Robust (Parameter) Design**
- **Tolerance Allocation**

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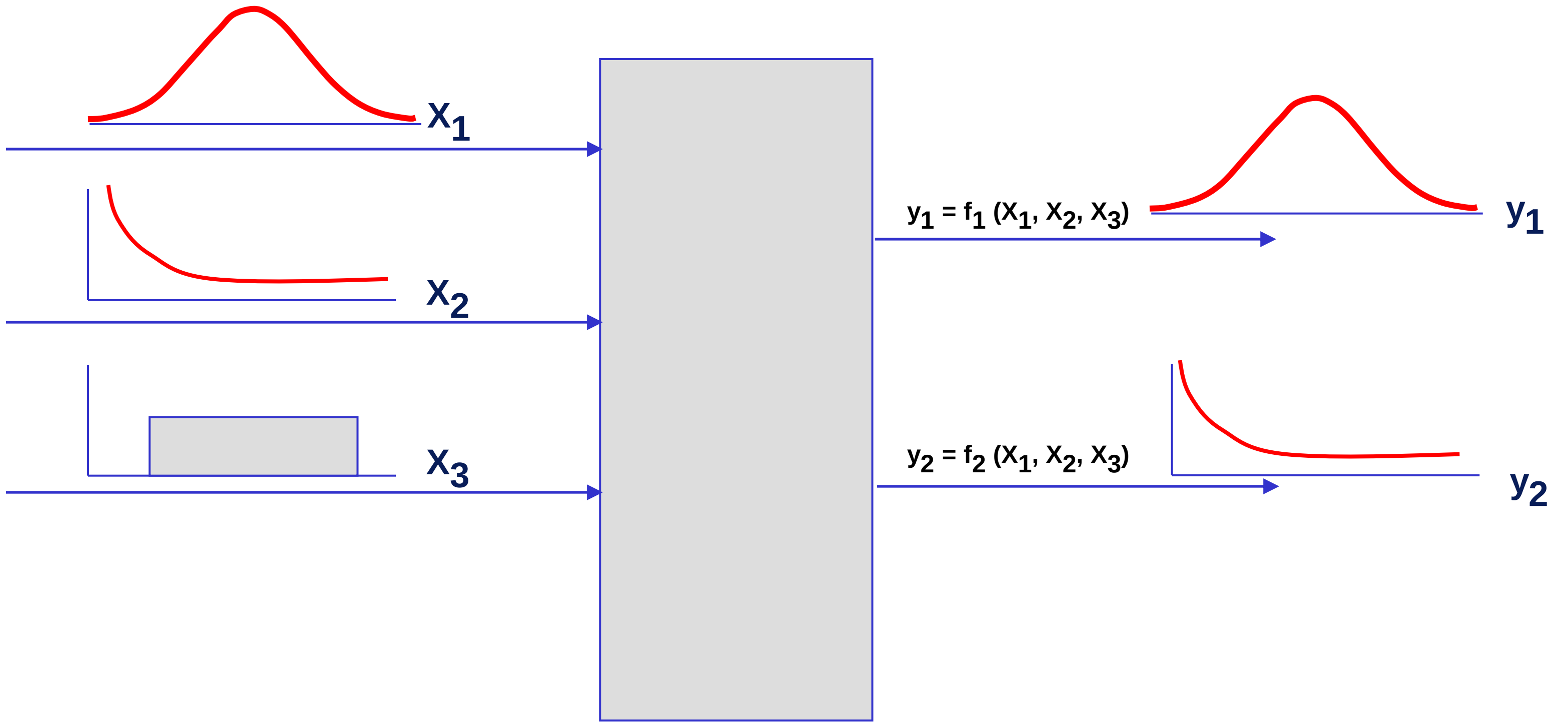
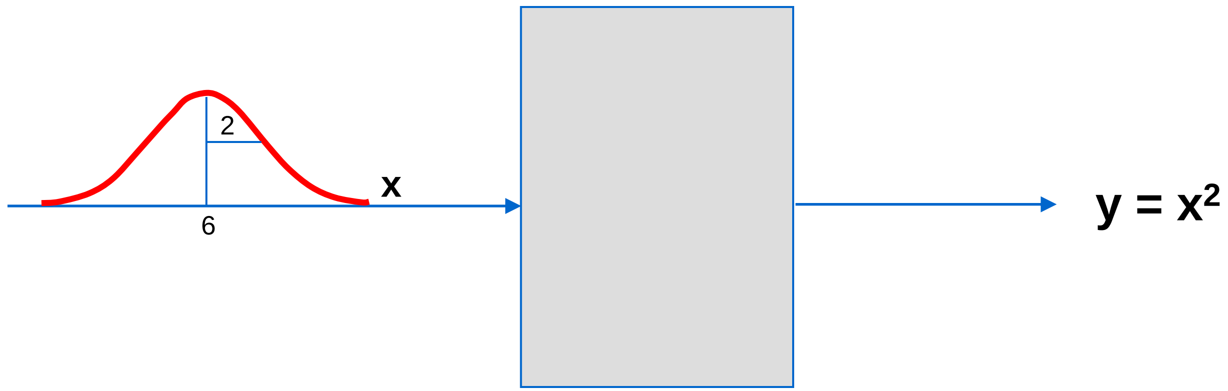
Expected Value Analysis (EVA)

EVA is the technique used to determine the characteristics of the output distribution (mean, standard deviation, and shape) when we have knowledge of (1) the input variable distributions and (2) the transfer functions.



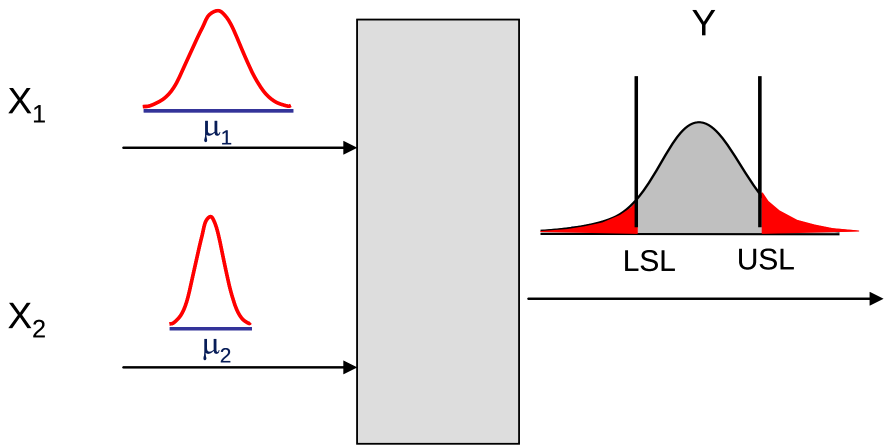
Expected Value Analysis Example



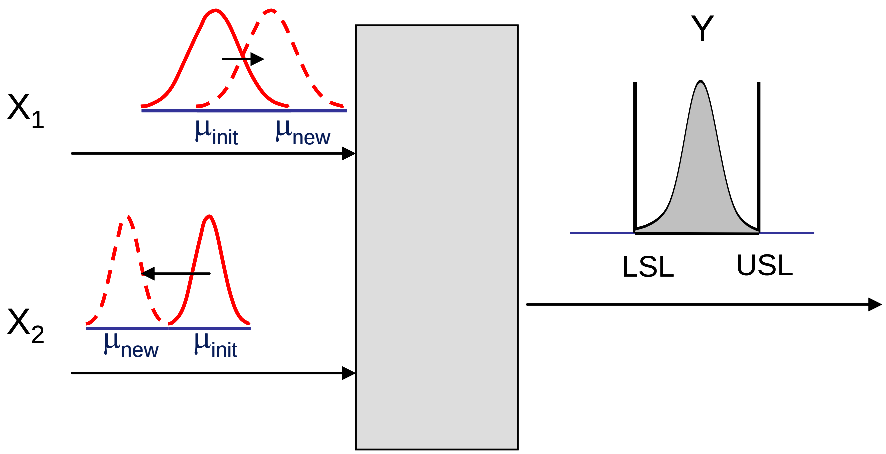
What is the mean or expected value of the y distribution?

What is the shape of the y distribution?

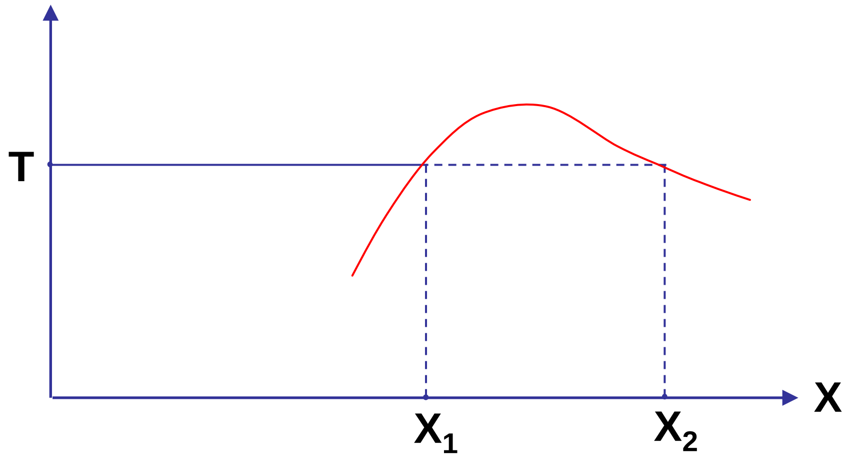
Parameter Design (Robust Design)



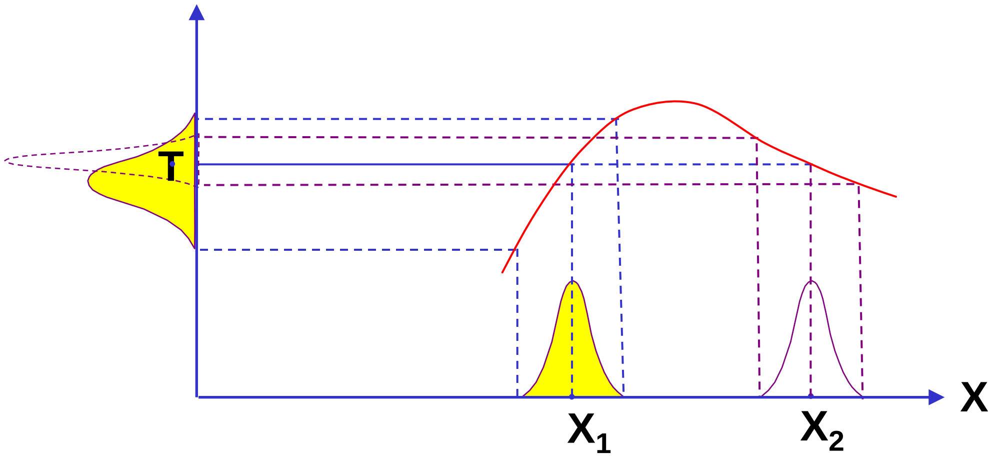
Process of finding the optimal mean settings of the input variables to minimize the resulting dpm.



Parameter Design (Robust Design)



If you're the designer, which setting for X do you prefer?



Changing the mean of an input may possibly reduce the output variation!

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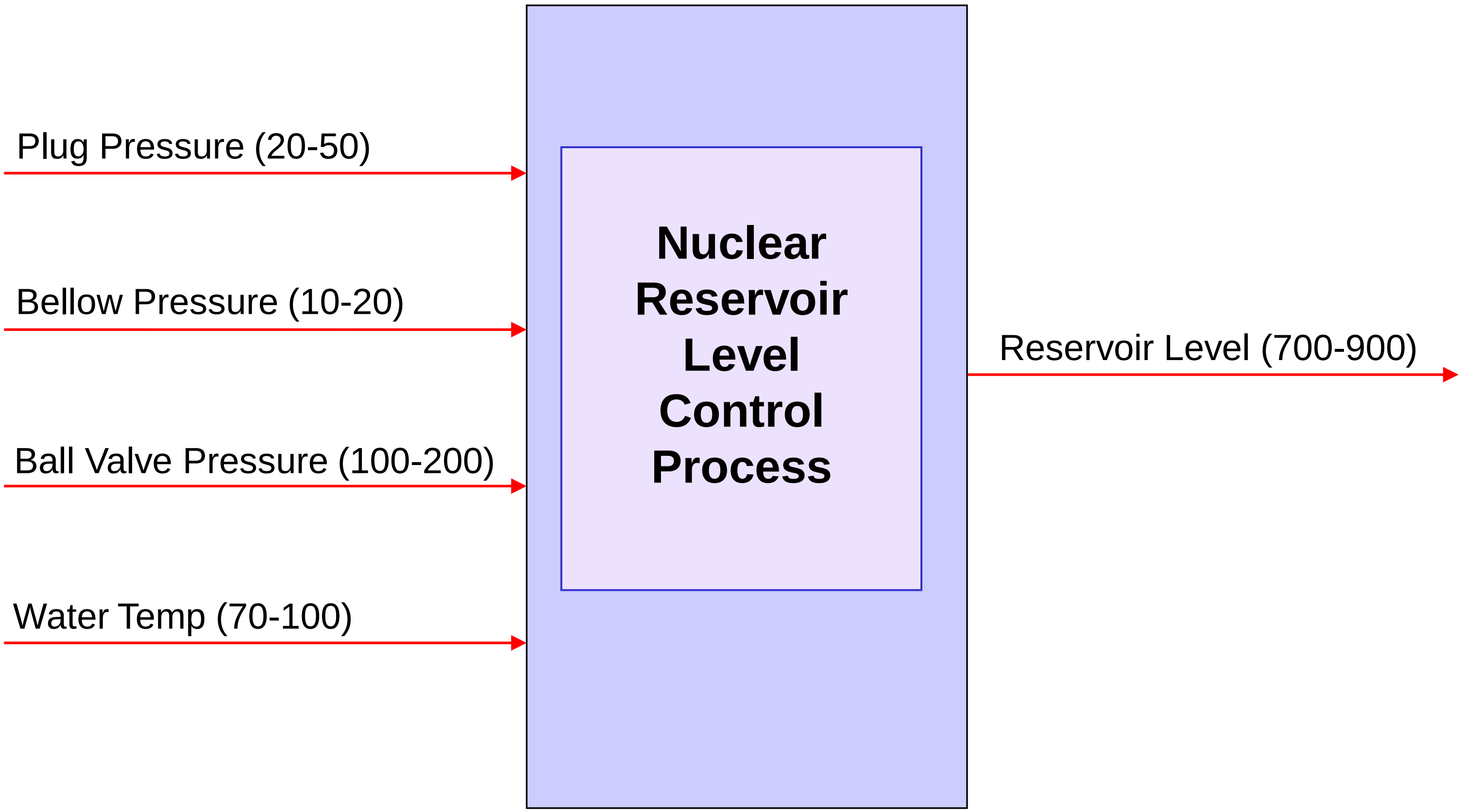
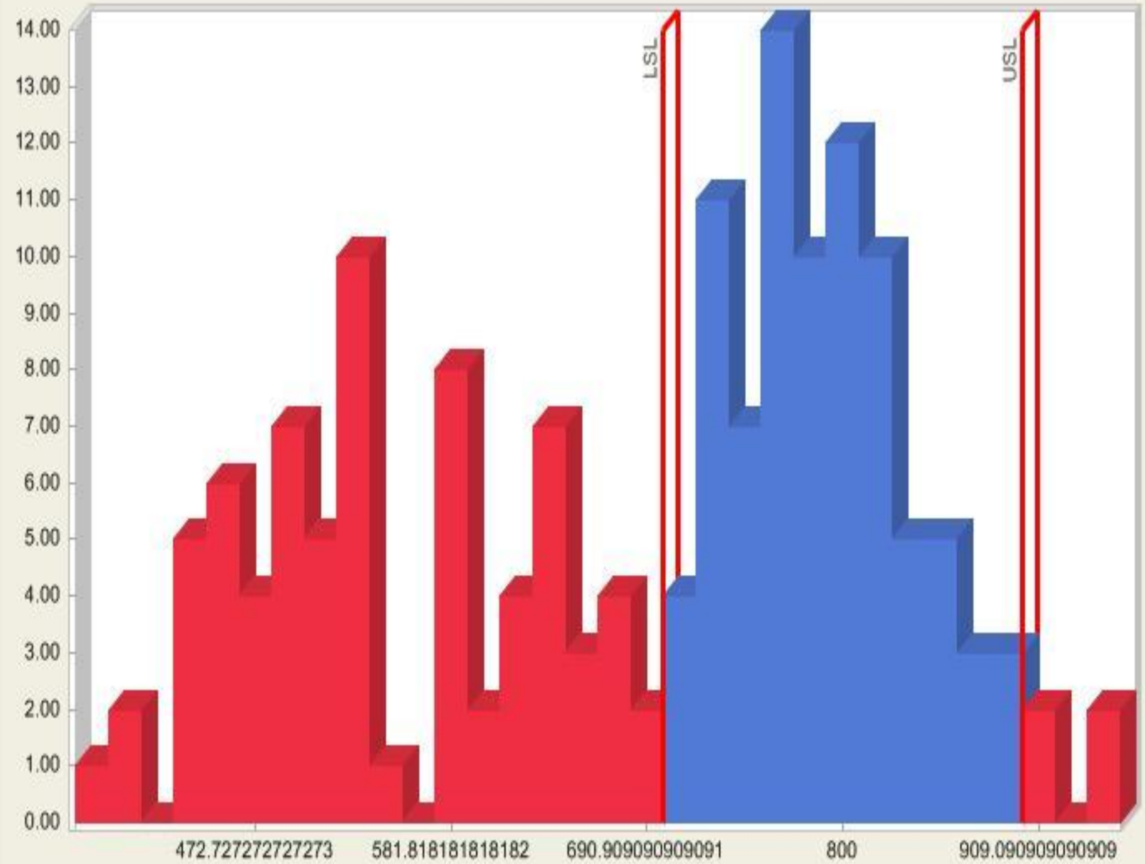
Robust (Parameter) Design Simulation* Example



* From **SimWare Pro** by Philip Mayfield and Digital Computations



Current Data

- n = 159
- Mean = 681.9
- Standard Deviation = 141.6
- LSL = 700
- USL = 900
- Cp = 0.2354
- Cpk = -0.0427
- DPM = 612,650
- Sig Cap = 1.214

Input Controls

Control Set 1

Plug Pressure (20 to 50)	Bellow Pressure (10 to 20)	Ball Valve Pressure (100 to 200)
50.0	12.00	145

Water Temp (Expensive to Control)

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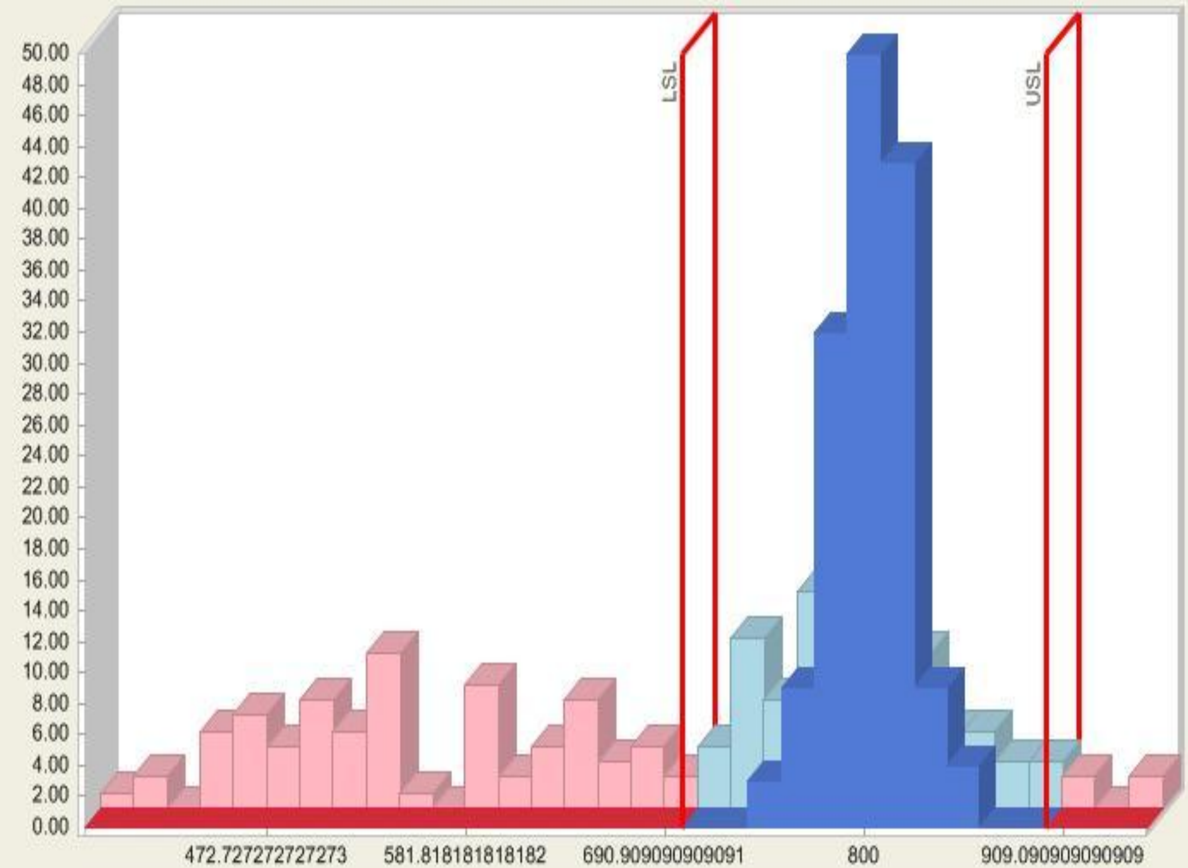

- Current Data
  - n = 150
  - Mean = 802
  - Standard Deviation = 21.56
  - LSL = 700
  - USL = 900
  - Cp = 1.546
  - Cpk = 1.516
  - DPM = 3.829
  - Sig Cap = 5.975
- Memorized Data
  - n = 159
  - Mean = 681.9
  - Standard Deviation = 141.6
  - LSL = 700
  - USL = 900
  - Cp = 0.2354
  - Cpk = -0.0427
  - DPM = 612,650
  - Sig Cap = 1.214

Input Controls

Control Set 1

21.0	20.00	137
Plug Pressure (20 to 50)	Bellow Pressure (10 to 20)	Ball Valve Pressure (100 to 200)

Water Temp (Expensive to Control)

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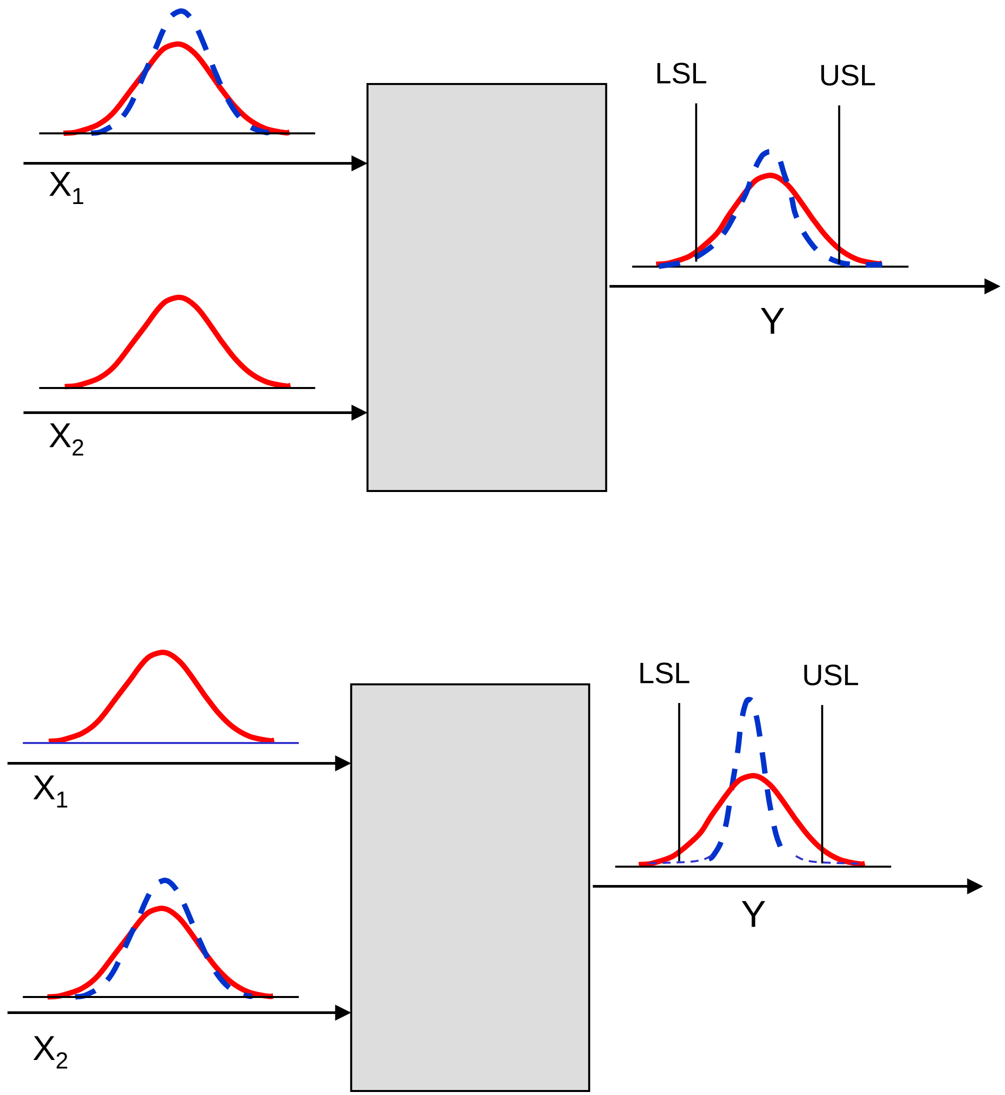
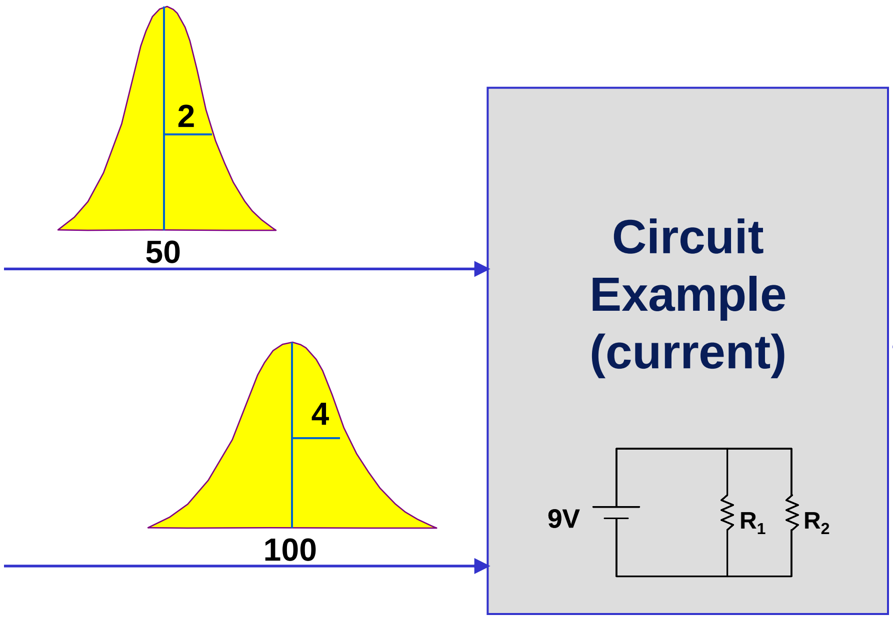
Tolerance Allocation



Which input standard deviations have the biggest effect on the output variation?

Tolerance Allocation Example



$$I = \frac{9(R_1 + R_2)}{R_1 \cdot R_2}$$

LSL = .255

USL = .285

Which resistor's standard deviation has the greater impact on the capability of I?

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Tolerance Allocation Example (cont.)

A reduction in R_1's standard deviation (sigma) significantly reduces the dpm while a reduction in R_2's standard deviation has a smaller effect.

Tolerance Allocation Table

Process Inputs			
Factor	Distro	First Parameter	Second Parameter
R1	Normal	50	2
R2	Normal	100	4

N = 10,000 (in dpm)		
current Table (Normal dpm)		
	R1	R2
-50% Sigma	2,897	45,852
-25% Sigma	21,912	53,427
-10% Sigma	46,150	58,483
Nominal	63,975	63,438
+10% Sigma	88,478	69,198
+25% Sigma	127,102	83,522
+50% Sigma	196,089	100,553

A reduction in R_1's standard deviation by 50% (from 2 ohms to 1 ohm) combined with an increase in R_2's standard deviation by 25% (from 4 ohms to 5 ohms) results in a dpm = 9,743.

(This result is not shown in the table.)

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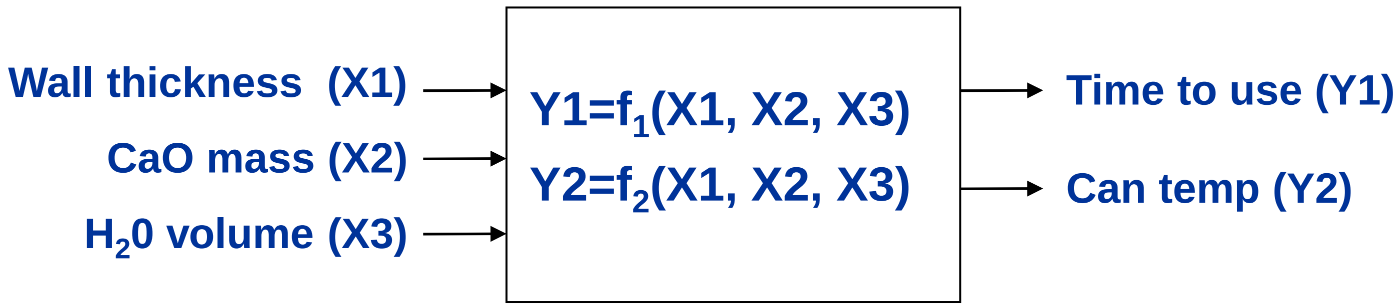
Case Study: Optimization Strategy



Optimize

How do we best set X1, X2, X3 to optimize Y1 and Y2?

- Expected Value Analysis (EVA)
  - a form of Monte Carlo simulation
- Robust Design methods
  - including computer-based Parameter Design
- Tolerance Allocation
  - via computer-based tolerance analysis

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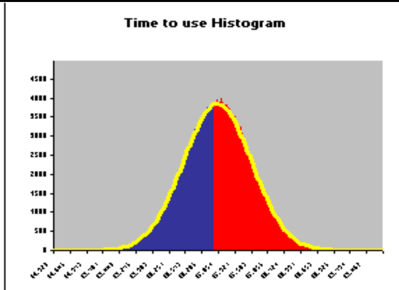
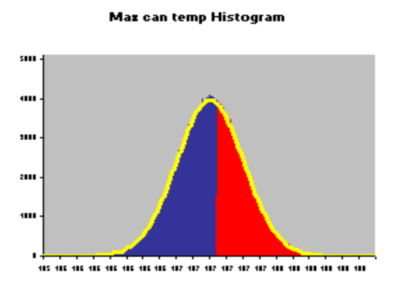
EVA – Monte Carlo Simulation

Process Inputs				
Factor	Distro	1st Parameter	2nd Parameter	Exper
Wall Thickness	Normal	0	0.089	0
CaO Mass	Normal	0	0.0765	0
H2O Volume	Normal	0	0.04123	0
Noise_Time to use	Normal	0	0.55075436	0
Noise_Max can temp	Normal	0	0.29526055	0

Process Outputs			
Name	Function	LSL	USL
Time to use	17.05547		17
Max can ten	106.9074		107

Expected Value Analysis





Optimize

Process Inputs			
Factor	Distro	First Parameter	Second Parameter
Wall Thic	Normal	0	0.089
CaO Mas	Normal	0	0.0765
H2O Volu	Normal	0	0.04123
Noise_Tir	Normal	0	0.550754
Noise_Ma	Normal	0	0.295261

Process Outputs	Time to use	Max can temp
# of Simulations	1,000,000	1,000,000
Mean	17.0426	106.9269
StdDev	0.5554	0.3073
LSL		
USL	17	107
Normal Distro Statistics		
KS Test p-Value (Normal)	0.211	0.217
dpm	530,572.305	405,965.585
Cpk	-0.026	0.079
Cp		
Sigma Level	-0.077	0.238
Sigma Capability	-0.077	0.238

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Parameter (Robust) Design

Parameter Ranges

Select the range for each input parameter

Wall Thickness	Mean	From	-1	to	1
CaO Mass	Mean	From	-1	to	1
H2O Volume	Mean	From	-1	to	1
Noise_Time to use	Mean	From	0	to	0
Noise_Max can	Mean	From	0	to	0

Help | Cancel | << Back | Next >> | Finish

Computing Optimal Parameters

Calculating .

Total Weight = 100.

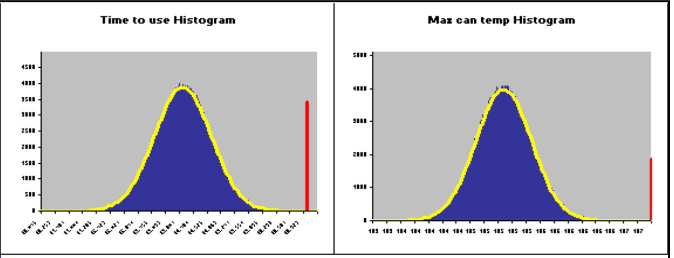
Inputs
Wall Thickness = -1.0
CaO Mass = -0.99998
H2O Volume = -0.93404
Noise_Time to use = 0.0
Noise_Max can temp = 0.0

Outputs
Time to use = 4.445 dpm
Max can temp = 0.03 dpm

Stop Parameter Design

Optimize

Expected Value Analysis



Process Inputs

Factor	Distro	First Parameter	Second Parameter
Wall Thic	Normal	-1	0.089
CaO Mas	Normal	-0.999978	0.0765
H2O Volu	Normal	-0.934036	0.04123
Noise_Tir	Normal	0	0.550754
Noise_Ma	Normal	0	0.295261

Process Outputs	Time to use	Max can temp
# of Simulations	1,000,000	1,000,000
Mean	13.9331	105.0354
StdDev	0.7062	0.374
LSL		
USL	17	107
Normal Distro Statistics		
KS Test p-Value (Normal)	0.0	0.0
dpm	7.039	.075
Cpk	1.448	1.751
Cp		
Sigma Level	4.343	5.252
Sigma Capability	4.343	5.252

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Tolerance Allocation

Tolerance Allocation Table

Process Inputs			
Factor	Distro	First Parameter	Second Parameter
Wall Thick	Normal	-1	0.089
CaO Mass	Normal	-0.9999782	0.0765
H2O Volur	Normal	-0.9340357	0.04123
Noise_Tim	Normal	0	0.5507544
Noise_Ma:	Normal	0	0.2952605

N = 1,000,000 (in dpm)

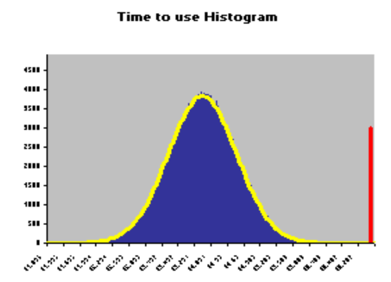
Time to use Table (Normal dpm)

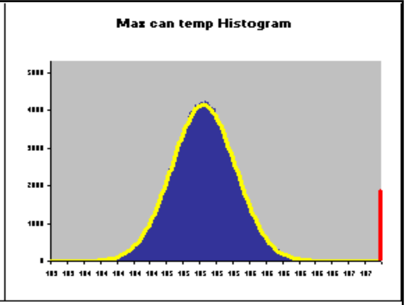
	Wall Thickness	CaO Mass	H2O Volume	Noise_Time to use	Noise_Max can temp
-50% Sigma	.1416	6.722	7.021	.00198	7.042
-25% Sigma	1.023	7.009	7.084	.1988	7.117
-10% Sigma	3.26	6.997	7.096	1.947	7.117
Nominal	7.048	7.134	7.056	6.943	6.989
+10% Sigma	14.48	7.197	7.074	21.25	7.055
+25% Sigma	40.3	7.344	7.065	89.5	6.995
+50% Sigma	171.0	7.621	7.085	531.3	7.061

Expected Value Analysis

By variance reduction

Optimize





Process Inputs			
Factor	Distro	First Parameter	Second Parameter
Wall Thic	Normal	-1	0.06
CaO Mas	Normal	-0.999978	0.0765
H2O Volu	Normal	-0.934036	0.04123
Noise_Tir	Normal	0	0.550754
Noise_Mε	Normal	0	0.295261

Process Outputs	Time to use	Max can temp
# of Simulations	1,000,000	1,000,000
Mean	13.9396	105.0247
StdDev	0.6279	0.3578
LSL		
USL	17	107
Normal Distro Statistics		
KS Test p-Value (Normal)	0.012	0.0
dpm	.546	.017
Cpk	1.625	1.84
Cp		
Sigma Level	4.874	5.521
Sigma Capability	4.874	5.521

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The Validate Phase

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The DFSS Process: Identify, Design, Optimize, Validate

– The **Identify** Phase
  – The DFSS Scorecard
  – Voice of the Customer (VOC)

– The **Design** Phase
  – Translating the VOC (Requirements Flowdown)
  – Concept Generation and Selection
  – Transfer Functions
  – Critical Parameter Management

– The **Optimize** Phase
  – Multiple Response Optimization
  – Expected Value Analysis Using Monte Carlo Simulation
  – Parameter Design
  – Tolerance Allocation

– The Validate Phase
  – High Throughput Testing

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The Validate Phase

- **Validating performance**
- **Performing sensitivity analysis**
- **Comparing Predicted capability with actual**
- **Gap analysis (reasons for lack of confirmation)**
- **Updating scorecards**

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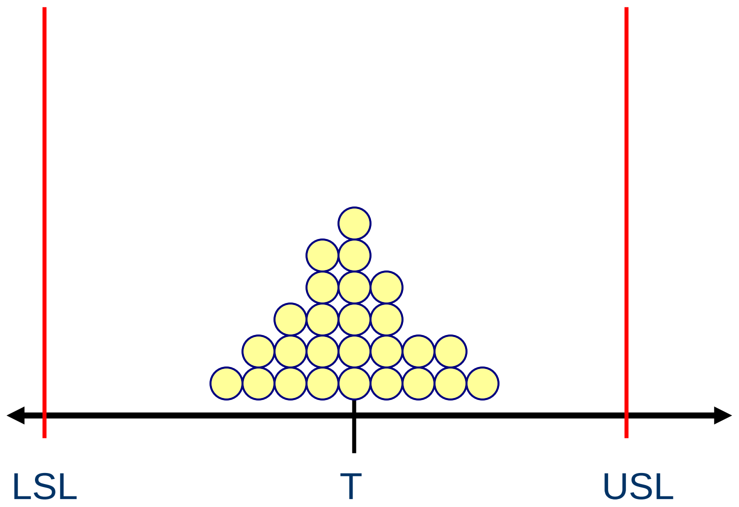
Validate

Critical parameters are validated against predictions from models.



<u>Methods may include</u>

- Prototypes
- Lab scale production
- Test-fixturing of subassemblies

If validation is poor ……… gap analysis!

Introduction to High Throughput Testing (HTT)

- A recently developed technique based on combinatorics
- Used to test myriad combinations of many factors (typically qualitative) where the factors could have many levels
- Uses a minimum number of runs or combinations to do this
- Software (e.g., ProTest) is needed to select the minimal subset of all possible combinations to be tested so that all 2-way combinations are tested.
- HTT is not a DOE technique, although the terminology is similar
- A run or row in an HTT matrix is, like DOE, a combination of different factor levels which, after being tested, will result in a successful or failed run
- HTT has its origins in the pharmaceutical business where in drug discovery many chemical compounds are combined together (combinatorial chemistry) at many different strengths to try to produce a reaction.
- Other industries are now using HTT, e.g., software testing, materials discovery, integration and functionality testing (see example on next page).

Submarine Threat Detection Example

- Suppose we want to perform a verification test with the following 7 input factors (with their respective settings):
  - Submarine Type (S1, S2, S3)
  - Ocean Depth (Shallow, Deep, Very Deep)
  - Sonar Type (Active, Passive)
  - Target Depth (Surface, Shallow, Deep, Very Deep)
  - Sea Bottom (Rock, Sand, Mud)
  - Control Mode (Autonomous, Manual)
  - Ocean Current (Strong, Moderate, Minimal)
- All possible combinations would involve how many runs in the test?
- If we were interested in testing all pairs only, how many runs would be in the test? Pro Test generated the following test matrix.

Submarine Threat Detection Example (cont.)

The following 15 test cases will test all pairwise combinations.

	Factor_A	Factor_B	Factor_C	Factor_D	Factor_E	Factor_F	Factor_G
Factor Name	Submarine Type	Ocean Depth	Sonar Type	Target Depth	Sea Bottom	Control Mode	Ocean Current
Case 1	S3	Deep	Passive	Very Deep	Mud	Manual	Minimal
Case 2	S1	Very Deep	Passive	Surface	Rock	Autonomous	Strong
Case 3	S2	Shallow	Active	Shallow	Rock	Manual	Moderate
Case 4	S2	Deep	Passive	Deep	Sand	Autonomous	Moderate
Case 5	S1	Shallow	Active	Surface	Sand	Manual	Minimal
Case 6	S1	Very Deep	Passive	Shallow	Mud	Autonomous	Minimal
Case 7	S3	Very Deep	Active	Deep	Mud	Manual	Strong
Case 8	S2	Very Deep	Active	Very Deep	Sand	Autonomous	Strong
Case 9	S3	Shallow	Passive	Shallow	Mud	Autonomous	Strong
Case 10	S3	Deep	Active	Surface	Rock	Manual	Moderate
Case 11	S1	Shallow	Active	Deep	Rock	Autonomous	Minimal
Case 12	S1	Deep	Passive	Very Deep	Rock	Manual	Moderate
Case 13	S2	Very Deep	Active	Surface	Mud	Autonomous	Moderate
Case 14	S3	Deep	Active	Shallow	Sand	Manual	Strong
Case 15	S2	Shallow	Active	Very Deep	Rock	Manual	Minimal

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HTT Applications

- **Reducing the cost and time of testing while maintaining adequate test coverage**

- **Integration and functionality testing**

- **Creating a test plan to stress a product and discover problems**

- **Prescreening before a large DOE to ensure all 2-way combinations are feasible before discovering, midway through an experiment, that certain combinations are not feasible**

- **Developing an "outer array" of noise combinations to use in a robust design DOE when the number of noise factors and settings is large**

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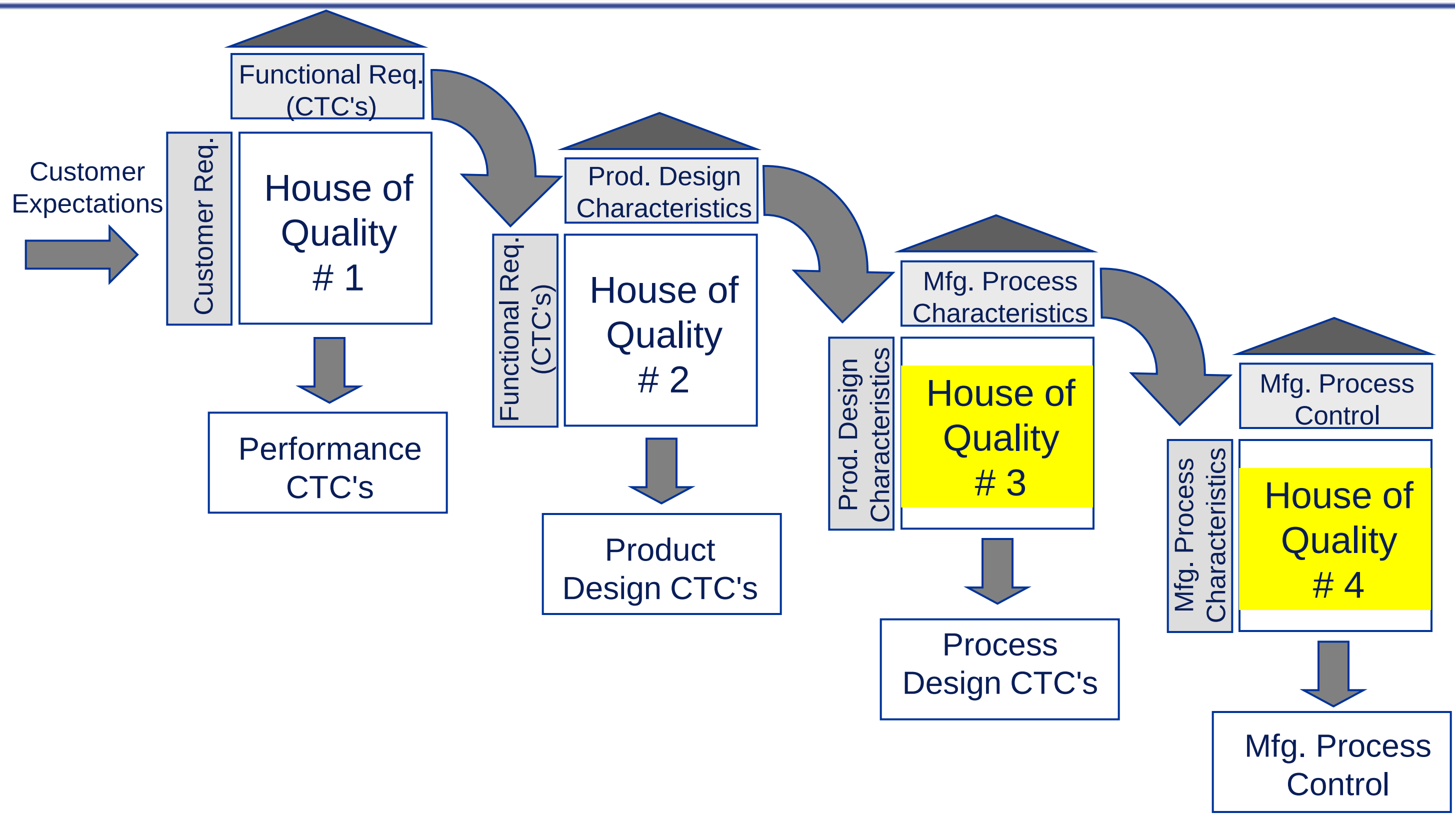
Requirements Flowdown Using QFD



Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability

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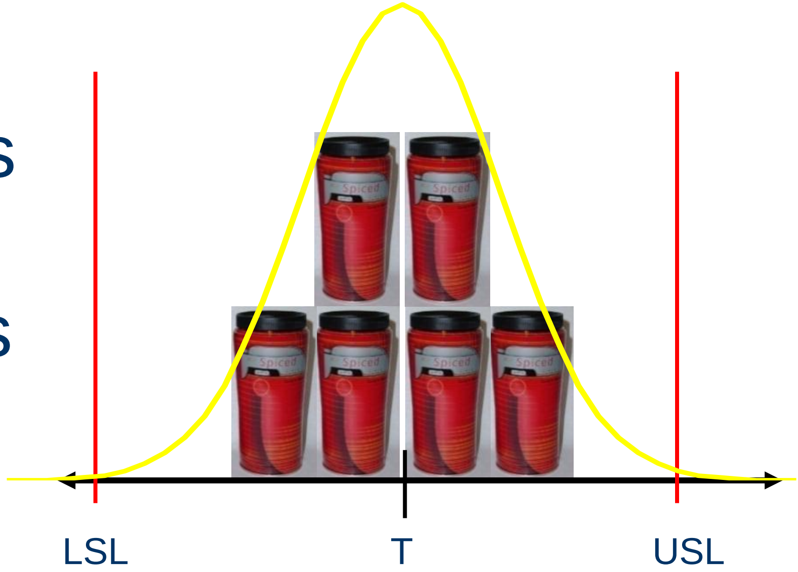
Case Study: Validation

Critical parameters are validated against predictions from models.



Methods may include

- Prototypes
- Lab scale production
- Test-fixturing of sub-assemblies

Validate

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3rd HOQ: Physical Domain → Process Domain

PPs (Process Domain)

DP (Physical Domain)

DP	wt	Mold Temp	Injection Speed	Clamp Force	Injection Pressure	Seamer roll force	.	
Wall thickness	3	9	3		3			
CaO mass	5	3	9					
H2O volume	4	3						
Button force	2							
.								
.								
Prioritized PPs		75	69	50	62	17	.	

Design Parameters are mapped to Process Parameters

Validate

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4^{th} HOQ: Process Domain → Process Control

Process Control →

PP (Process Domain) ↓

PP	wt	Temp Xbar-R Chart	Machine SOP	Machine 1 SOP	Machine 2 SOP	Force IMR Chart	.	
Mold Temp	5	9	3		3			
Injection Speed	4	3	9					
Clamp Force	2							
Injection Pressure	3							
Seamer roll force	1							
.								
Prioritized PCs		67	71	19	45	67	.	

Process Parameters are mapped to Process Controls

Mfg.

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Methods & Tools Used in Case Study

	QFD	Axiomatic Design	TRIZ	Analytical Modeling & Simulation	LSS/DFSS
Identify	VOC ↓ HOQ1 ↓ CTCs (FPs)	CUSTOMER DOMAIN ↓ FUNCTIONAL DOMAIN	8 PATTERNS SYSTEMS VIEW		SURVEYS INTERVIEWS FOCUS GROUPS PAIRWISE COMPARISON BASES
Design	CTCs (FPs) ↓ HOQ2 ↓ DPs	FUNCTIONAL DOMAIN ↓ (VIA AXIOMATIC DESIGN) ↓ PHYSICAL DOMAIN	FUNCTIONAL MODEL TC & PC ALGORITHMS RESOURCES	FEA, CFD: ANSYS FLUENT COSMOS	Functional Analysis System Technique (FAST)
Optimize	DPs	INDEPENDENCE & INFORMATION OPTIMIZATION (DECOUPLING)	FUNCTIONAL MODEL TC & PC ALGORITHMS		DOE / EVA MONTE CARLO / DS PARAMETER DESIGN TOLERANCING
Validate	DPs ↓ HOQ3 ↓ PPs	PHYSICAL DOMAIN ↓ PROCESS DOMAIN	TC & PC ALGORITHMS	CONFIRMATION	HYPOTHESIS TESTS CONFIRMATION
Mfg.	PPs ↓ HOQ4 ↓ PC	PROCESS DOMAIN ↓ PROCESS CONTROL	TC & PC ALGORITHMS		SPC CONTROL PLANS POKA YOKE

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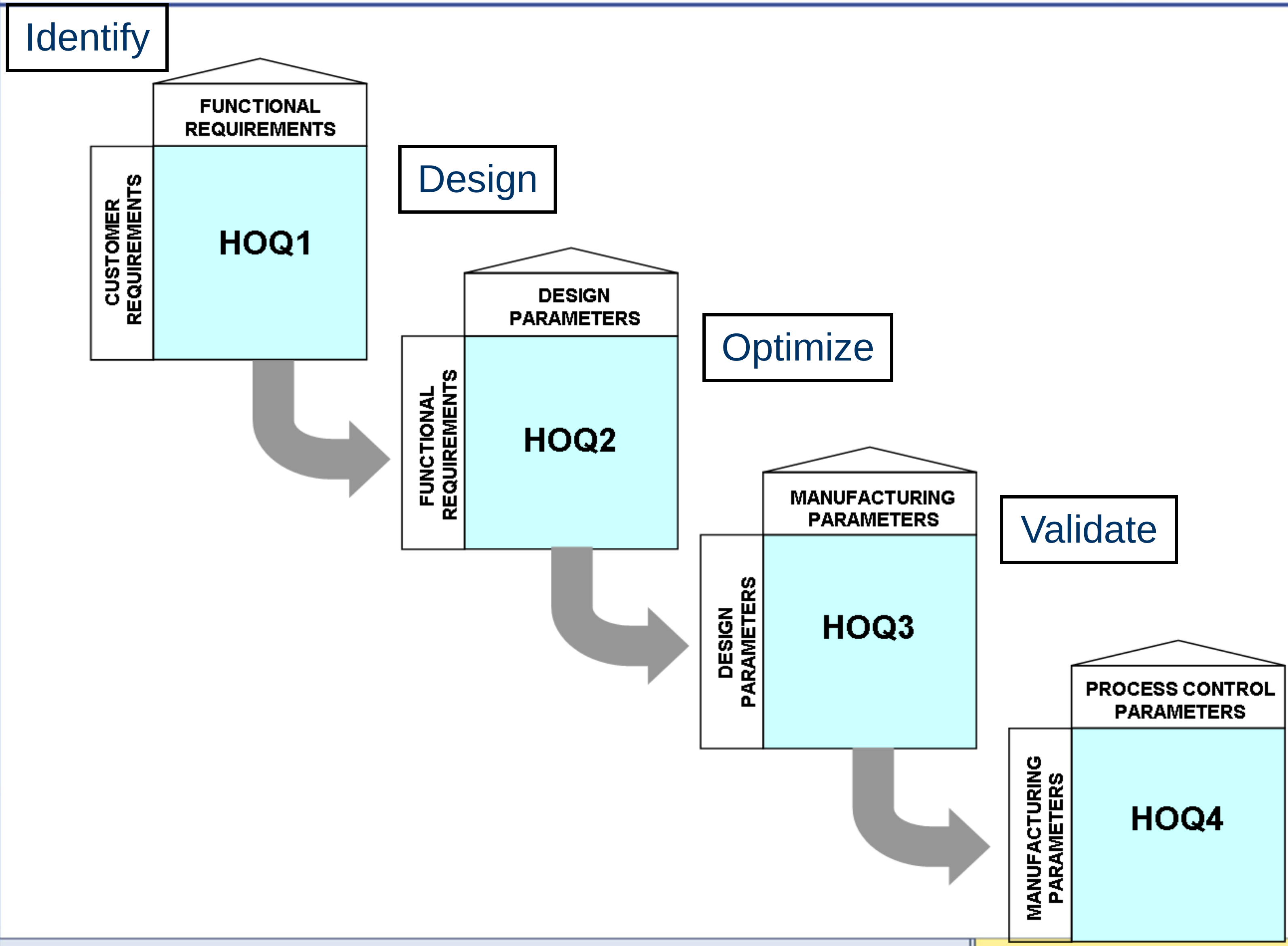
The Original DFSS (Design for Six Sigma)



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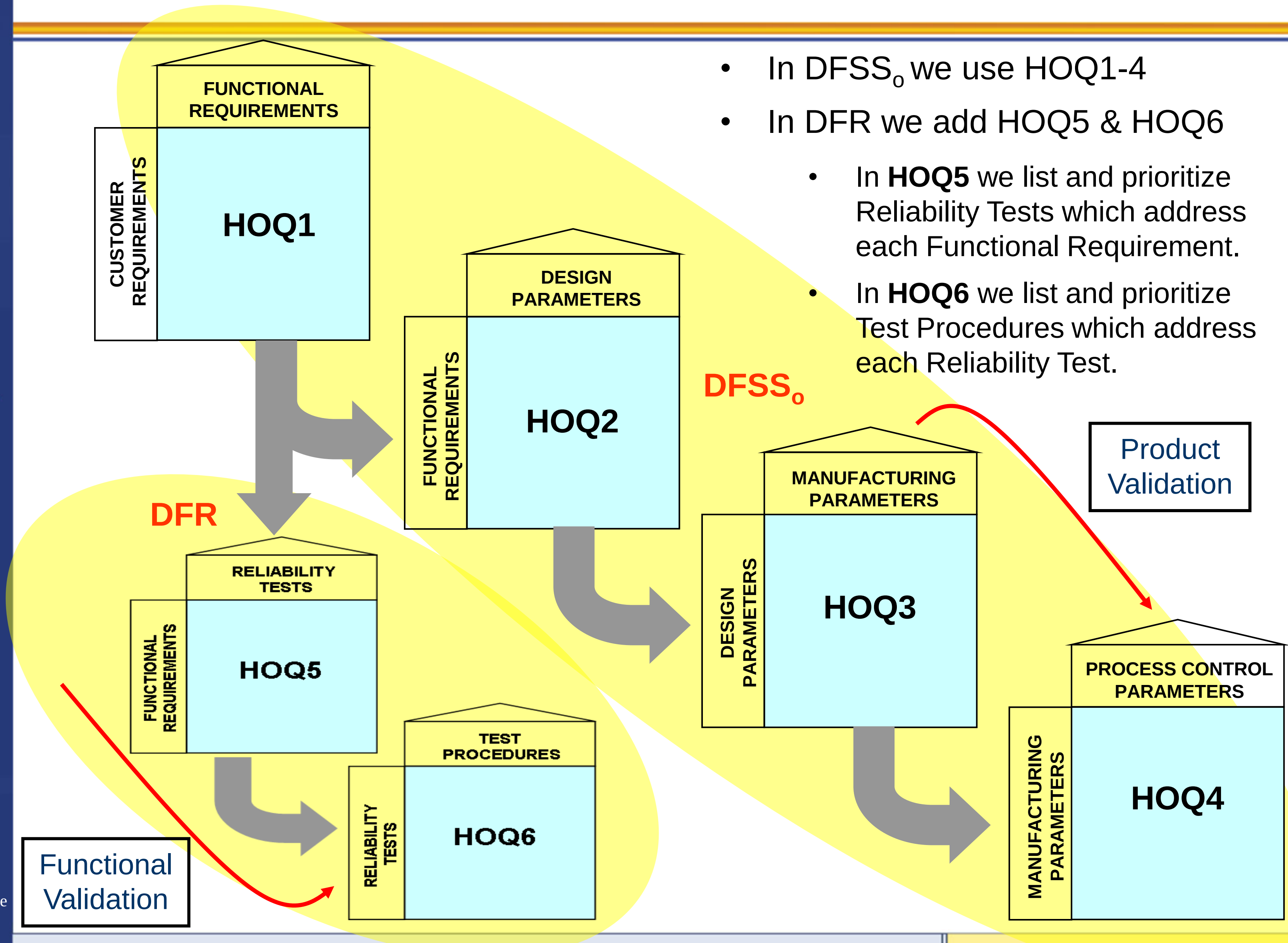
Design for Successful Systems ($DFSS_o$+DFR)

- In $DFSS_o$ we use HOQ1-4
- In DFR we add HOQ5 & HOQ6
  - In **HOQ5** we list and prioritize Reliability Tests which address each Functional Requirement.
  - In **HOQ6** we list and prioritize Test Procedures which address each Reliability Test.



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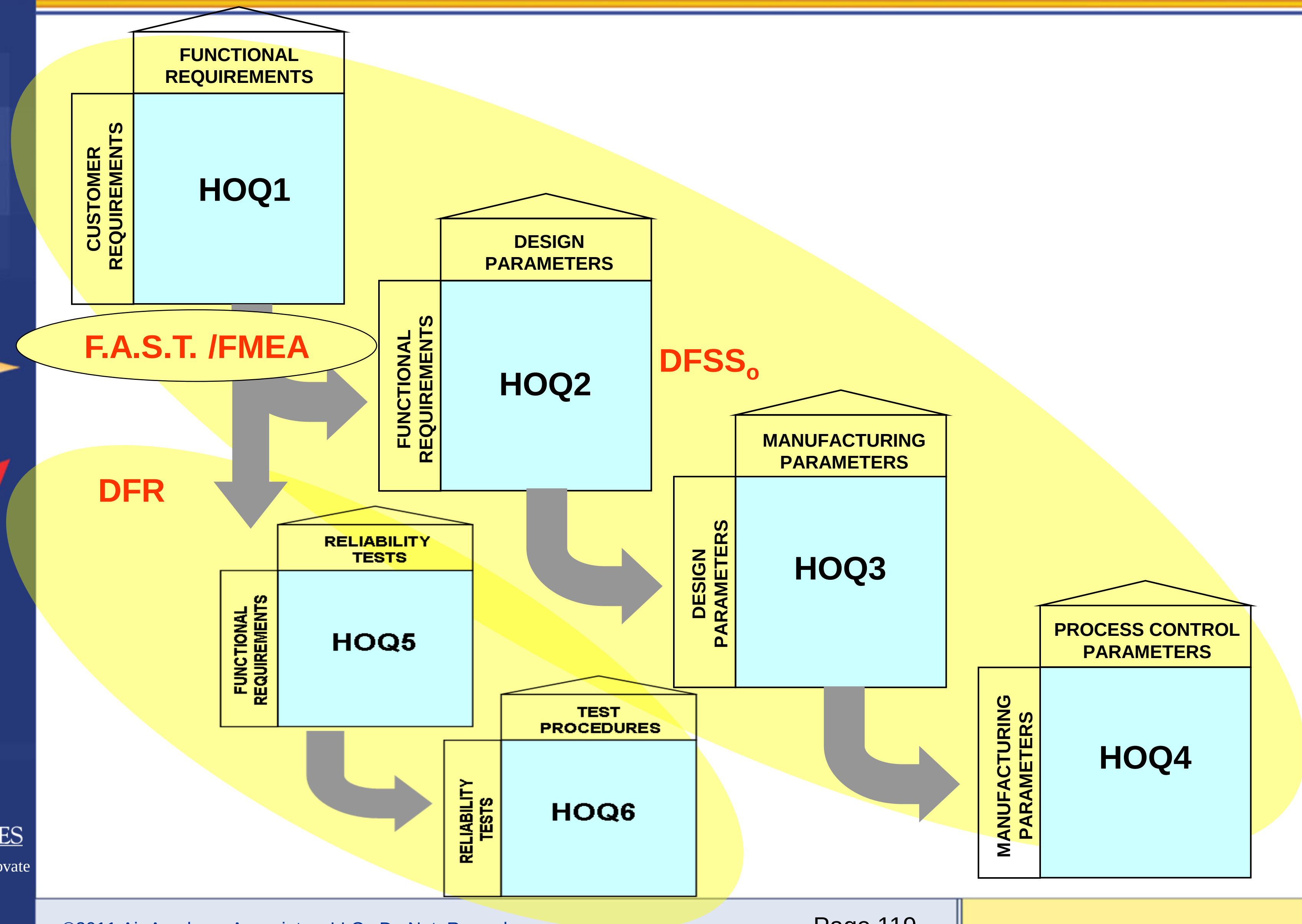
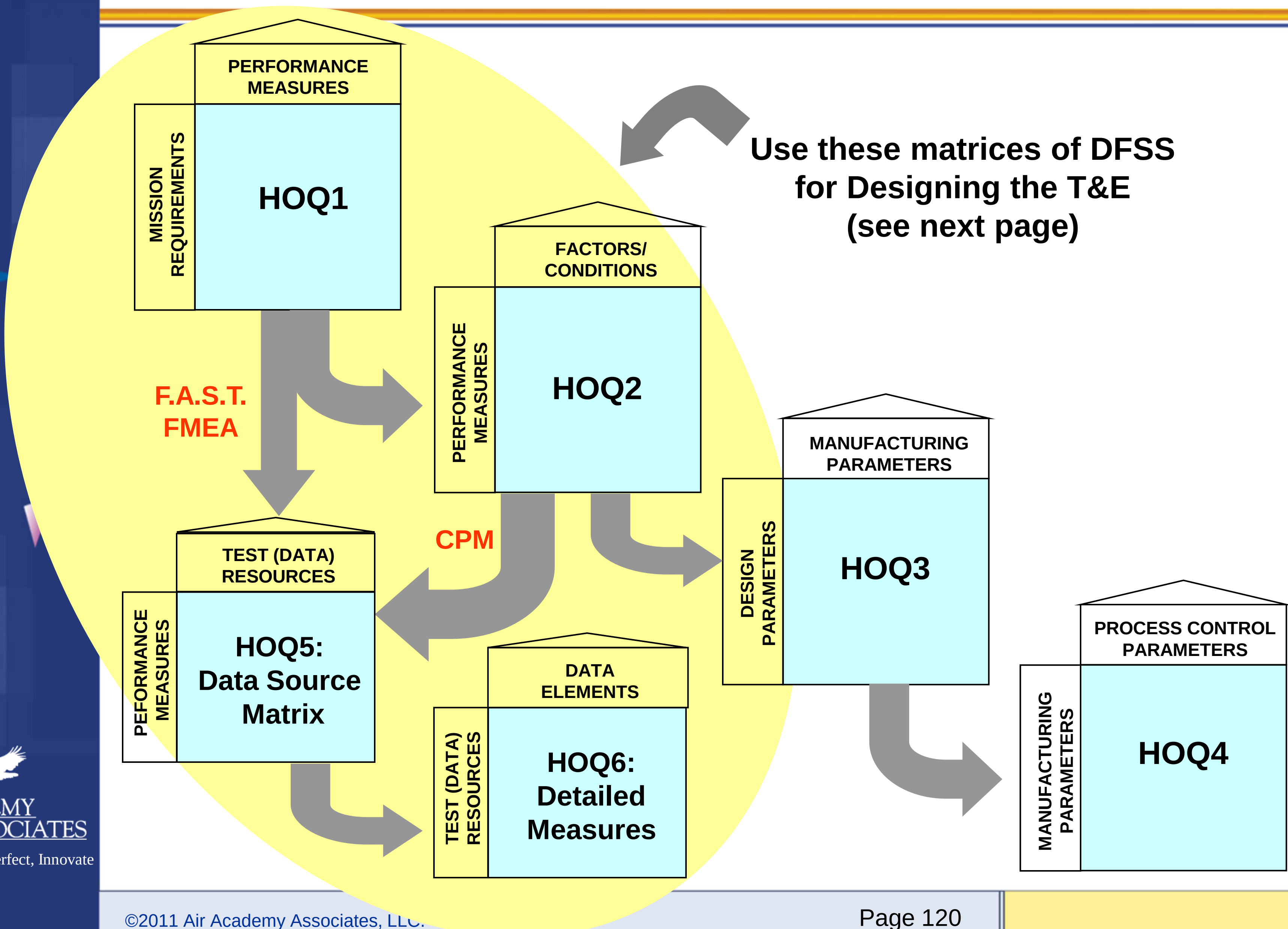
Evolution of Design for Successful Systems

($DFSS_o$ + DFR + FAST/FMEA)



MBT&E with Design for Successful Systems



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Steps for Designing the Test and Evalution*

Tools and Methods from DFSS that can help accomplish these steps are in parentheses:

- **Develop the measures of effectiveness from the task capabilities and the measures of performance from the system attributes. (HOQ 1)**
- **Determine the operational factors and conditions. (HOQ 2)**
- **Develop linkages between measures and COIs. (CPM)**
- **Complete linkages from measure-to-system-to-task. (CPM)**
- **Assign one or more data sources to each evaluation measure. (HOQ 5)**
- **Determine the operational conditions that can or cannot be addressed by the identified data sources. (HOQ 2, CPM, and HOQ 5)**
- **Develop detailed measure design. (HOQ 6)**
- **Develop design of experiments. (HOQ 2, CPM, HOQ 5, HOQ 6)**

*** These steps are taken from Chris Wilcox's MBT&E Tutorial (page 25) at NDIA T&E 2010.**

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DFSS Success Stories

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Partial Listing of Who Has Used Our DFSS Process and Tools

- Xerox
- Gates Rubber Company
- Hyundai
- Timken
- GE Medical Systems
- Medtronic
- St. Jude Medical
- Sony
- John Deere
- Delphi
- Sensis

- Nokia
- Bose Corporation
- PerkinElmer
- Samsung
- ATMI
- Pollak Industries
- Sandia National Laboratory
- Abbott Laboratory Diagnostics
- GlaxoSmithKline
- General Dynamics Land Systems

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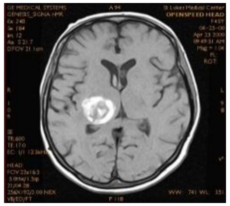
GEMS LightSpeed™ CT Scanner

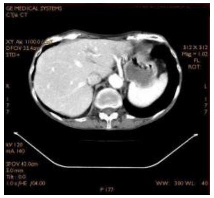
GE's First DFSS System ('98): Full Use of Six Sigma/DFSS Tools

- Key customer CTQs identified
  - Image quality
  - Speed
  - Software reliability
  - Patient comfort
- Disciplined systems approach: 90 system CTQs
- 33 Six Sigma (DMAIC) or DFSS projects/studies
- Scorecard-driven
- Part CTQs verified before systems integration

Leading-Edge Technology

- World's first 16-row CT detector
- Multi-slice data acquisition
- 64-bit RISC computer architecture
- Long-life Performix™ tube





Results

Better image quality
  - Earlier, more reliable diagnoses
  - New applications; vascular imaging, pulmonary embolism, multi-phase liver studies,…
- Much faster scanning:
  - Head: from 1 min to 19 sec (9 million/yr)
  - Chest/abdomen: from 3 min to 17 sec (4 million/yr)
- Clinical productivity up 50%
- 10x improvement in software reliability
- Patient comfort improved – shorter exam time
- Development time shortened by 2 years
- High market share; significant margin increase

"Biggest breakthrough in CT in a decade," Gary Glazer, Stanford

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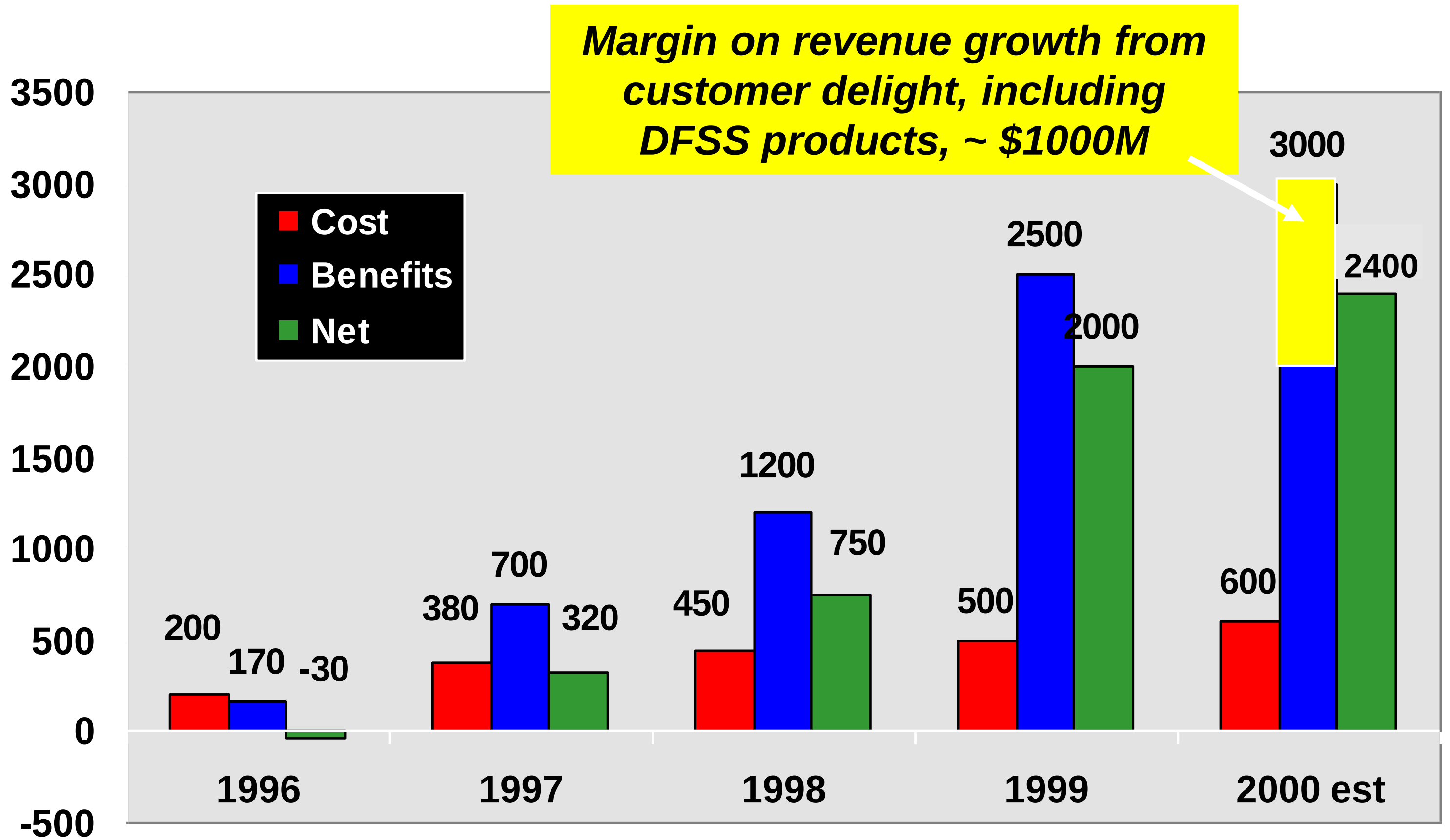
GE's Six Sigma/DFSS Financial Benefits: '96 - '00



- Major impact on the bottom line
- Significant benefits from customer delight, including DFSS

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Xerox Develops New Paper

Wall Street Journal:
Xerox Develops a 'Green' Paper, But Will Firms Add it to Fold?
By William M. Bulkeley
July 30, 2007; Page B3

Xerox has invented an environmentally friendly copy paper that costs less. The new cut-sheet "High-Yield Business Paper" requires half as many trees, fewer chemicals and less energy to manufacture and it weights less, reducing postage and trucking costs. Merilyn Dunn of InofTrends suggests the paper will be used for transactions such as invoices and phone bills where people don't care about long-term archiving of documents. Xerox and others have tried to use cheap newsprint in copiers and laser printers in the past, but "you always had catastrophically bad results related to the curl in a digital printer," said Steve Simpson, Xerox's vice president in charge of paper and supplies. Bruce Katz, a paper technologist in Xerox's research facility in Webster, said he was able to overcome the curling problem by figuring out how to make cellulose fibers in the paper line up evenly, so they would shrink at the same rate when the toner fusing process took place.

Note: Bruce Katz, a Xerox DFLSS GB, used the DesIgNNOVATION™ methods to accomplish this.

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Photoreceptor Belt Tensioning System

iSixSigma Magazine
July/August 2007, pp 47-55
By Bob Hildebrand, Xerox DFLSS Black Belt

The Xerox Corp. designs, manufactures and markets iGen3, a color printer that can produce photo-quality prints at 110 pages per minute. When the current iGen3 was to be modified, the engineering team was tasked with redesigning the belt tensioning mechanism on the photoreceptor into a smaller package without adjusting the length of the belt. The redesign had to take several noise factors into account. The outcome of the project was a design that met the constraints placed on it by the system. This IDOV project is a practical example of how Design for Lean Six Sigma (DFLSS) can bring about the best option available in a constrained design.

Please see the referenced article for a detailed presentation of this case study.

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Some Results From Other DFSS Studies

Accelerated Testing of a Proprietary Product

- Time to qualify process changes reduced from a year to 5 weeks – 860% test cost reduction
- 5 years benefit of $48.5M based on accelerated placement of lower cost units

Regression Analysis to Predict Life of a Proprietary Product

- $2M ΔNPV Improvement
- 24 hours to develop right material
- Overall length of project: 3 months (vs. 2 years using traditional approach)
- Life expectancy improvement: over 4x!

Modeling to Reduce Development Costs and Improve TTM

- Matured the new design to last for >5 Million cycles in 6 months
- Demonstrated that following DFSS can accelerate Time to Market
- Established the importance that all QMS parts go through the DFSS process

Identifying Critical Parameters

- 25% cost reduction of part: $3M savings
- Leveraged the new accurate measuring process across product lines
- Short term solution in two months, long term took a year

Supply Problem Resolution Using Simple Hypothesis Testing

- $2M immediate savings and saved the product from being withdrawn from field
- Took just four months to resolve a problem that had lingered for 10 years
- Gained control of infant mortality (i.e., failures within first 6 months)

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Using DFSS to Improve Reliability Growth

FEF = Fix Effectiveness Factor

Historical data from reliability growth models indicates an overall average of .7
(Source: Larry Crow's RAMS 2011 presentation, page 68)

Using a DFSS FEF of at least .9, we can see that the number of iterations can be reduced substantially to achieve the same goal.

	FEF = .7	FEF = .9
Start	1,000,000	1,000,000
After 1^{st} Iter.	300,000	100,000
After 2^{nd} Iter.	90,000	10,000
After 3^{rd} Iter.	27,000	1,000
After 4^{th} Iter.	8,100	100
After 5^{th} Iter.	2,430	10
After 6^{th} Iter.	729	1
After 7^{th} Iter.	218	.1
After 8^{th} Iter.	65	.01
After 9^{th} Iter.	20	.001

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