pdma product development and management association

Systems Engineering and Design for Six Sigma:

The Missing Pieces within PDMA Best Practices

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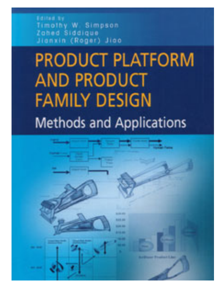
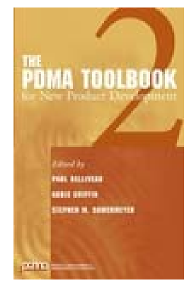
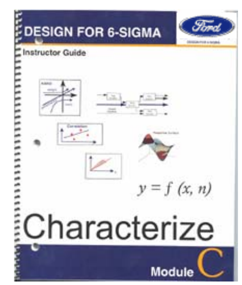
Robust Systems and Strategy LLC

- Robust and reliable modular platform and technology development consulting
- Training, consulting and project work on all aspects of product development
  - Market strategy for new technology
  - Robustness and flexibility of new technology
  - Platform modularity definition
- Experience
  - NPD Consulting
  - Associate Professor, MIT
  - DFSS Six Sigma Master Black Belt







Winner

Overview

- Design for Six Sigma
- Modeling and Analysis in Systems Engineering
- Results

What is DFSS?

What if you were asked not to develop your product instantly, but to "do it right"?

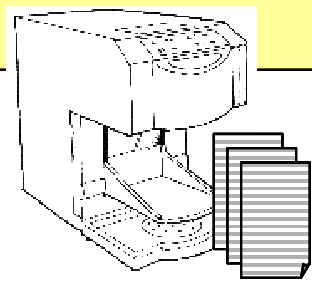
A "shift from deterministic to a probabilistic design culture"

(from DFSS: 15 Lessons Learned; *Quality Progress*; Jan. 2002)

Historical Development Process

Development Process: Do it quick!

Define Overall Requirements



Design

Alpha

Beta

PPU

BUILD, TEST, FIX CYCLES!

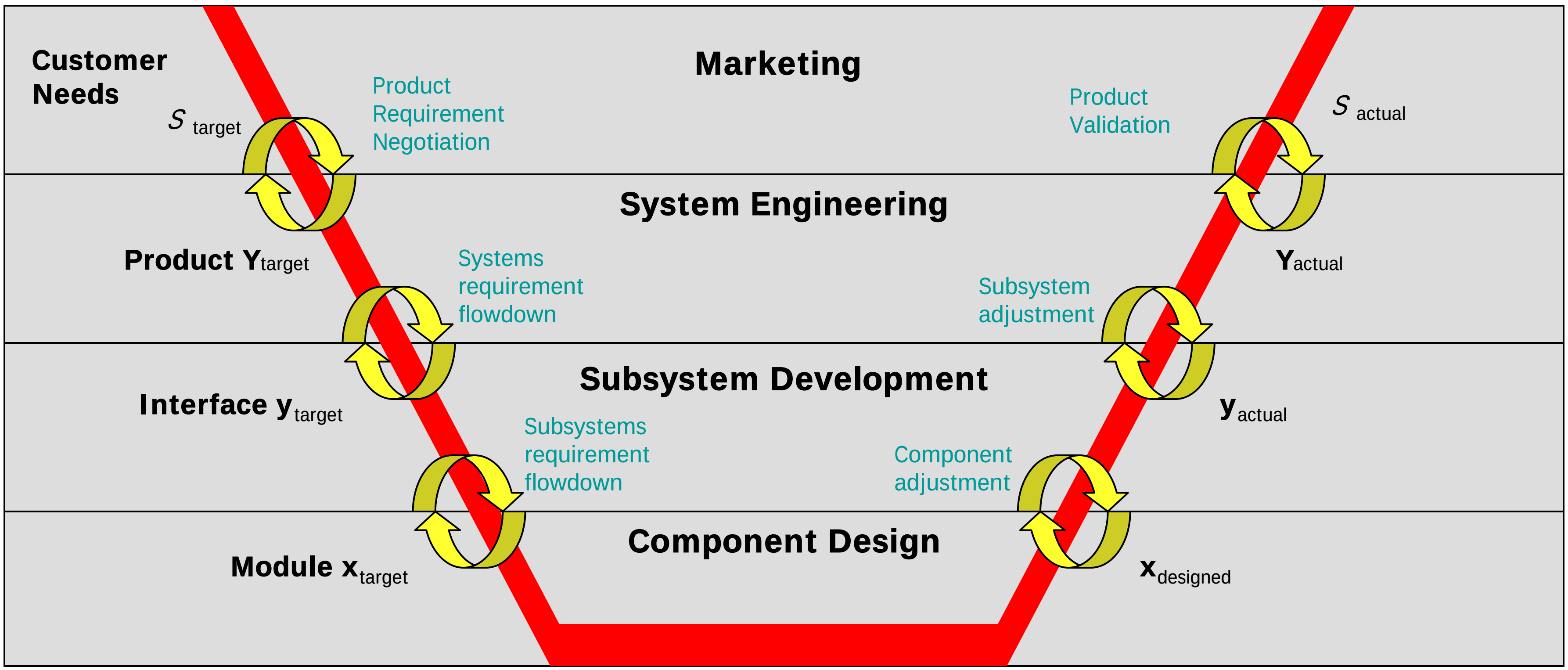
BUILD, TEST, FIX CYCLES!

Product Evolution



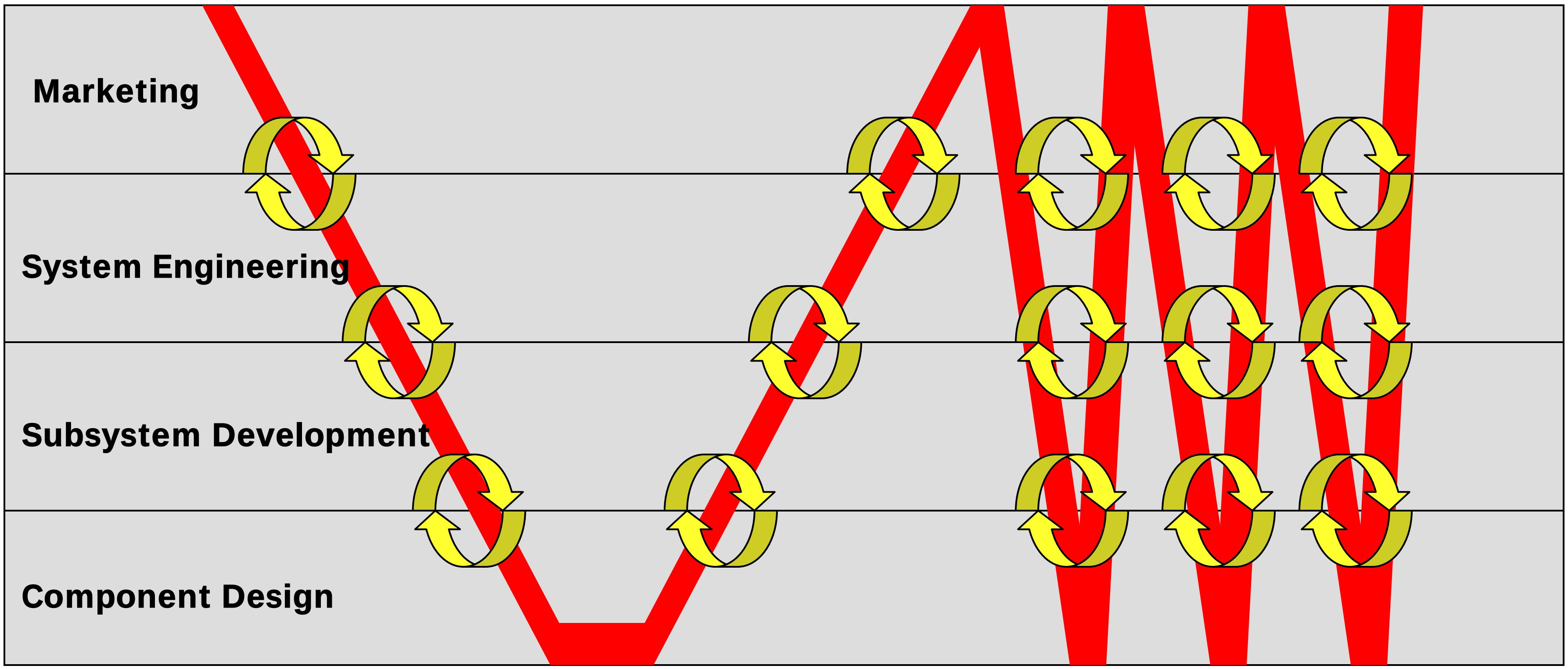

Modern System Engineering

- Flowdown requirements allocation…



- …Build up experimental verification

Problems...



- Built – Test – Fix, Build – Test – Fix, ...

Quality: What it Means

The cost of fixing a single defect:

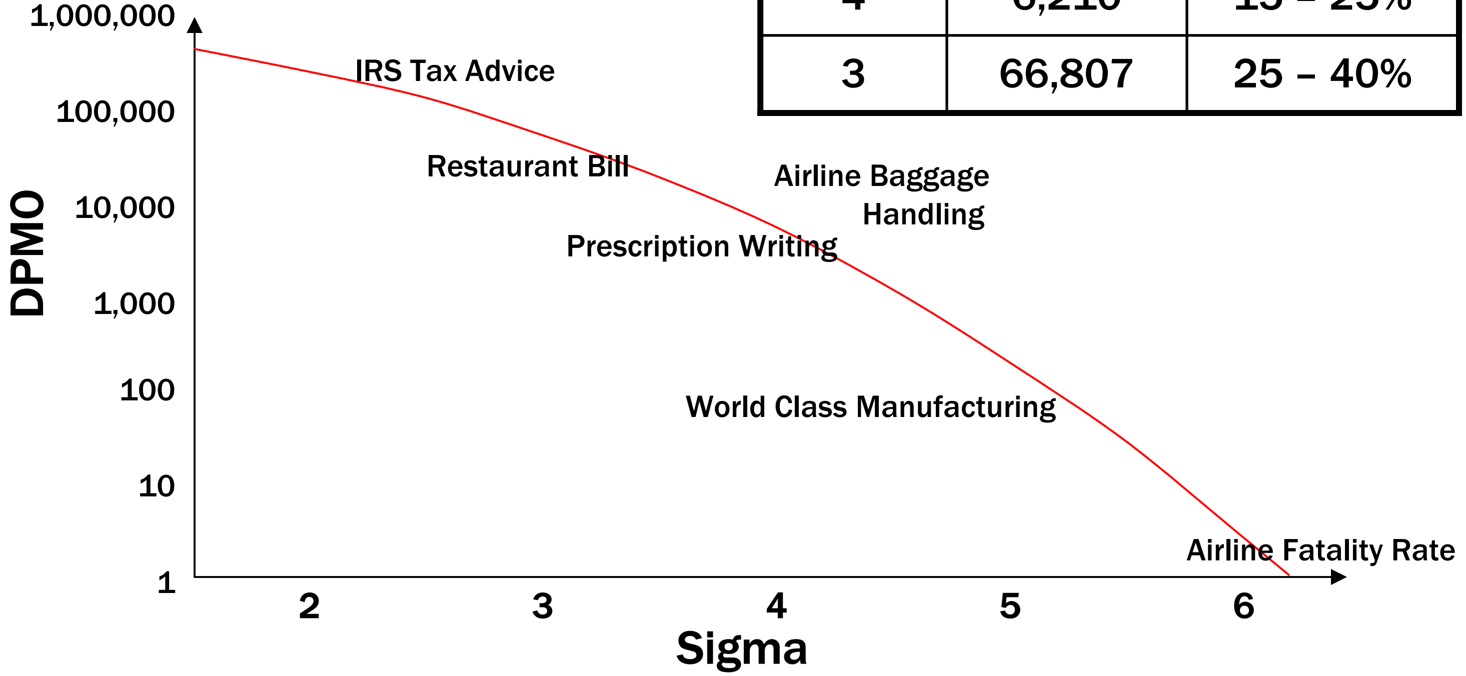
- $35 during the design phase
- $177 before procurement
- $368 before production
- $17,000 before shipment
- $690,000 on customer site

Mr. Hiroshi Hamada, President of Ricoh

Source: *European Community Quarterly Review*, Third Quarter 1996

Capability: What is Six Sigma?

Sigma	Defects / Million	Cost as % Sales
6	3.4	< 1%
5	233	5 – 15%
4	6,210	15 – 25%
3	66,807	25 – 40%



Most companies operate at ≤ 4 sigma

What are your warrantee and service costs?

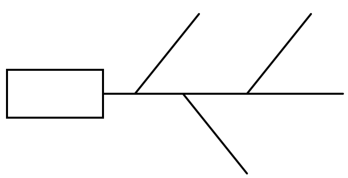
Operations & Production Six Sigma

Define → **Measure** → **Analyze** → **Improve** → **Control**

Define

What's the problem
Clarify it
- Defect data
- What defects
- What productn steps

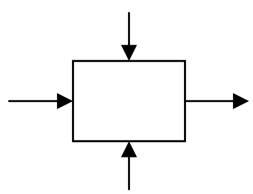
Tools:
- Fishbone diagrams
- Observation
- Discussion



Measure

How to measure it
- Not defect counts
- Output variation
- Measurement system

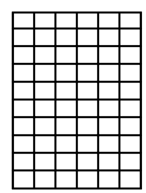
Tools:
- P-diagram
- MSA
- Data collection



Analyze

What changes it
- Controllable
- Noise
- Signals

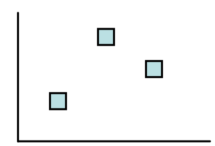
Tools:
- DoE
- Robust Design



Improve

What to change
- Controllable

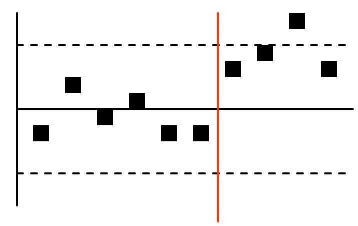
Tools:
- Robust Design
- Signal to Noise
- CPM
- Stat. Tolerances



Control

How to keep it there
- Control plans

Tools:
- SPC
- MSA



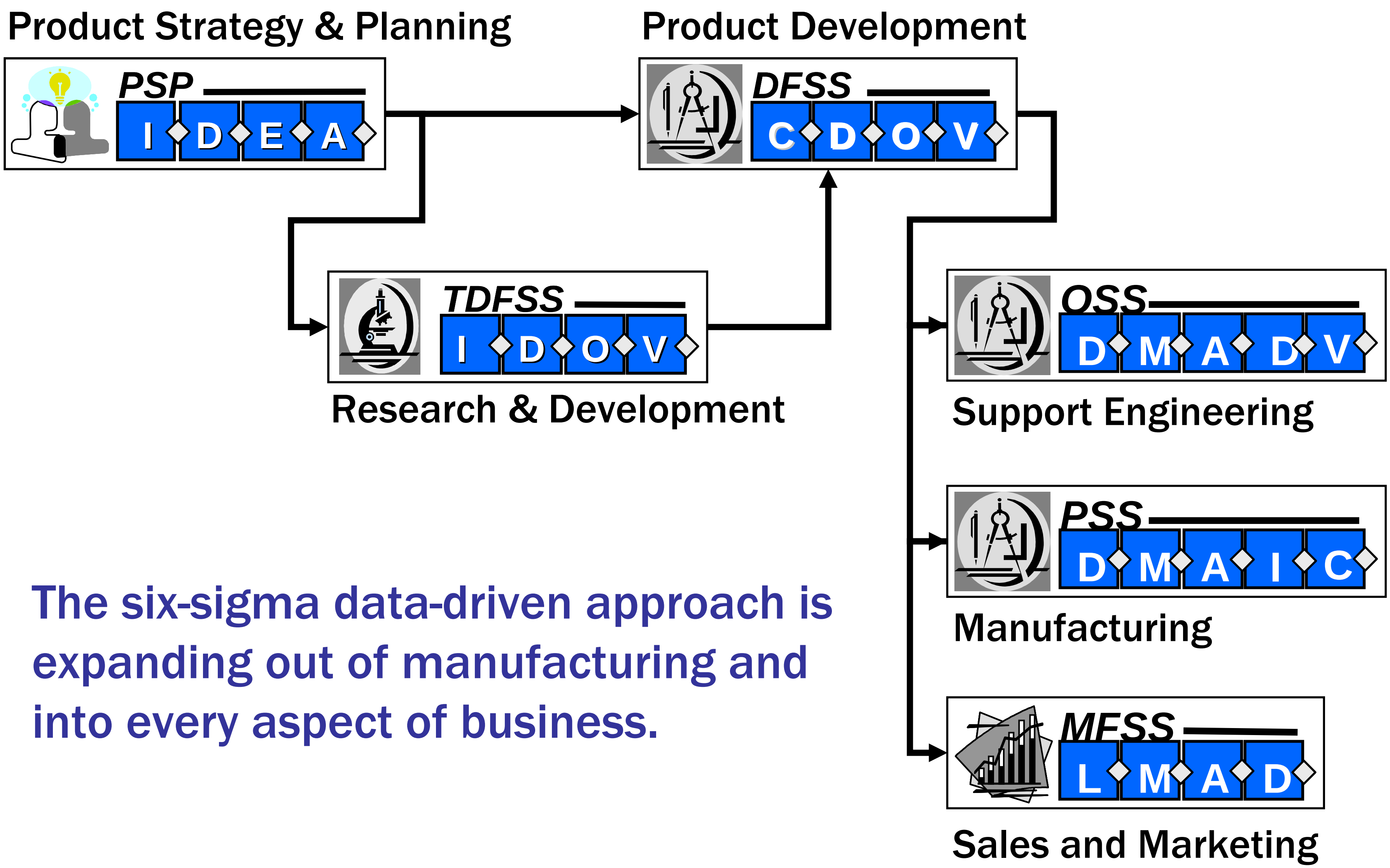
Generates "bottom line" financial value by eliminating Cost-Of-Poor-Quality (COPQ) in production & business transactions

It works

- GE published a net benefit of $2 billion in its 1999 annual report
- Jack Welch, has said Six Sigma will save his company $12 billion over five years and will add $1 to its earnings per share

- Allied Signal has saved $1.2 billion in direct costs since 1994
- Asean Brown Boveri (ABB) saved $898 million each year for two years

Six Sigma Across the Enterprise



The six-sigma data-driven approach is expanding out of manufacturing and into every aspect of business.

Improve Existing or New Products First?

- Bob Galvin, CEO of Motorola stated that…

  If he would start six sigma again,
  he would focus on product development
  rather than manufacturing.

- Galvin's view is that mfg. process improvement is often the result of poor product development.

- With any corporate Six Sigma implementation, there occurs a natural evolution out into the organization

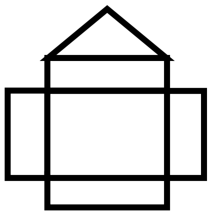
- R & D offers the highest leverage against the cost of poor quality. DFSS.

Design for Six Sigma

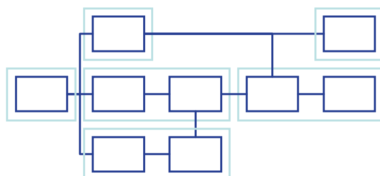
Generates "top line" financial value by providing new products with no problems and thereby generate new revenue.

VOC

QFD

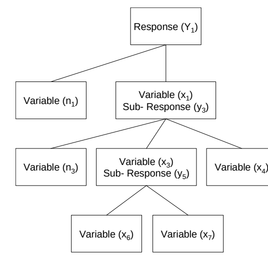


Functional Architecture

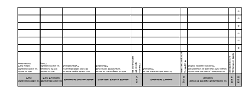


Module Concept Gen & Sel

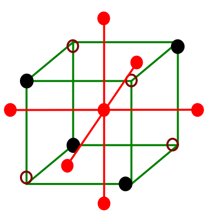
CPM



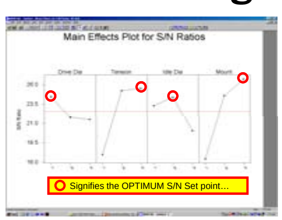
FMEA



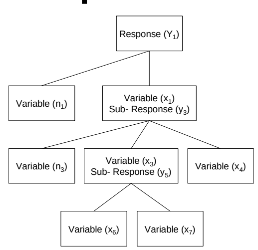
Design of Experiments



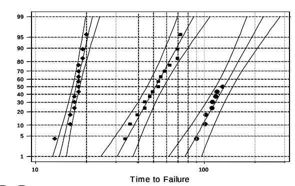
Robust Design



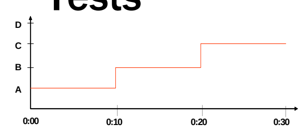
Capability Equations



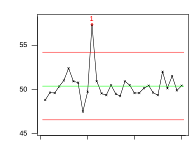
Reliability Prediction



System Stress Tests



Capability Verification



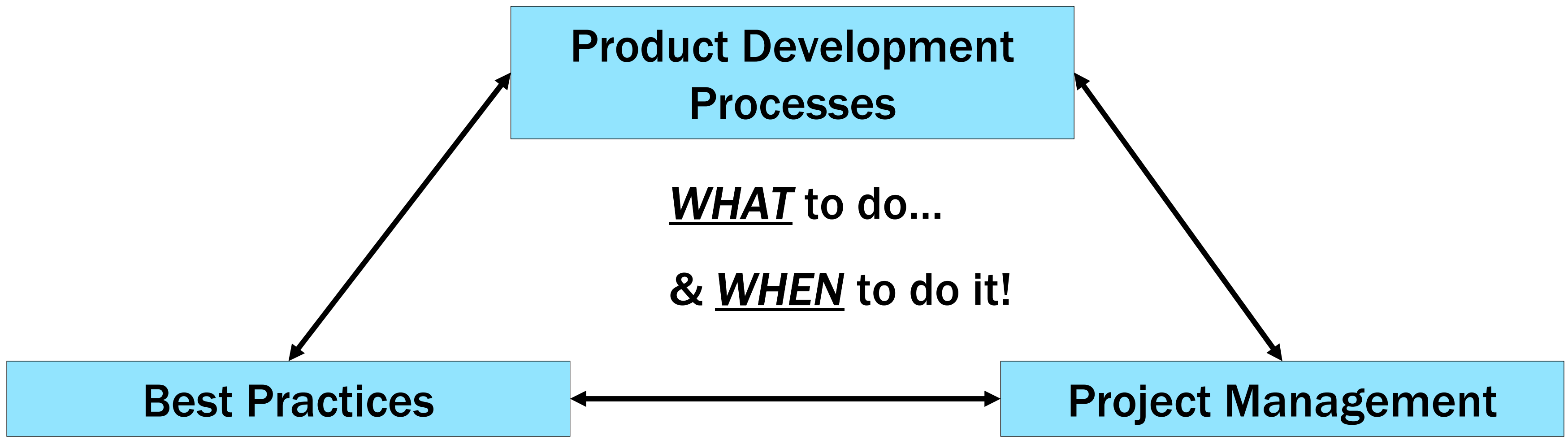
What's Different

- Statistical tools for design
- Eliminate or accommodate variability
- Functionally Parametric Designs – Data and Equations
- Shared Focus – Critical Parameter Management
- Process Scorecards
- Test Planning
- Subsystems first
- Experimentation over regions of the design space

Result:

1. **No surprises, scrambles, ECOs at manufacturing launch.**
2. **Confidence against any surprise at manufacturing launch.**

Key Elements in Improving Product Development

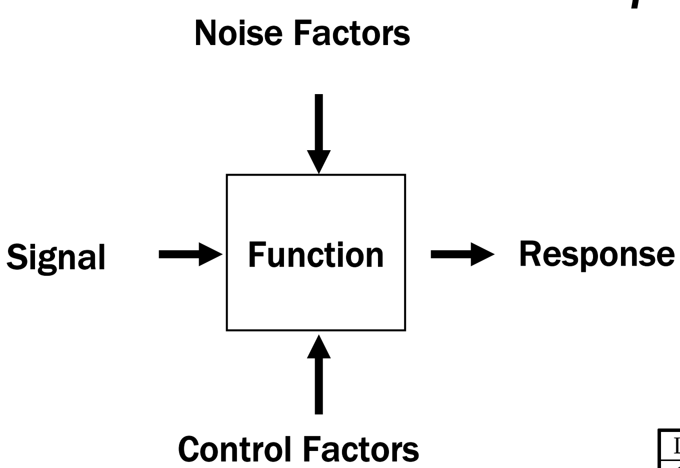


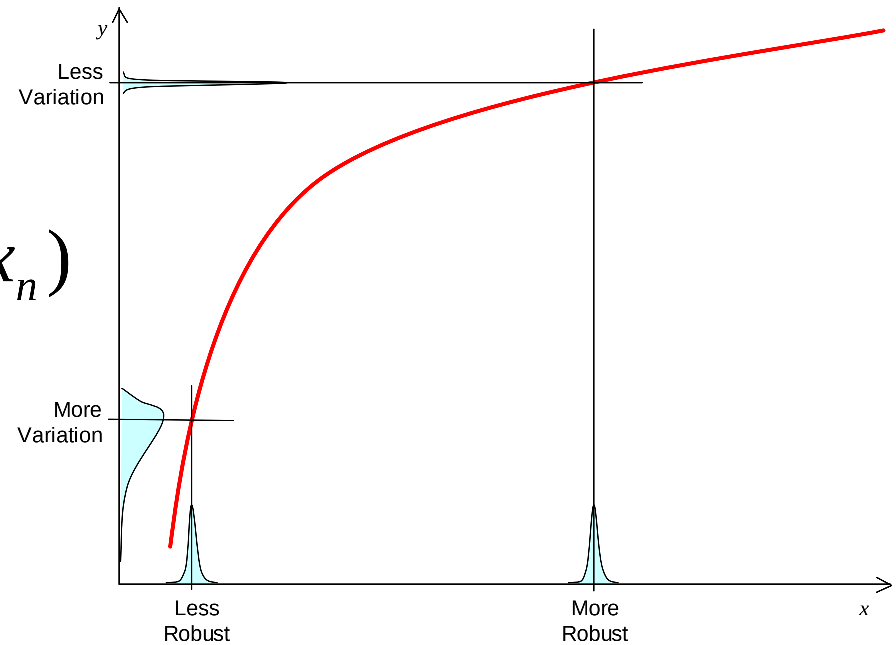
- Schedule your project activities *with risk and backup planning* project management tools
- Map specific project activities to standard work with Phases & Gates of an *End-to-End Development Process*
- Insert appropriate *Tools & Best Practices* with your detailed Project Activities

1. Best Practices: Designed Experiments and Robust Design

Generate *equations* to relate responses to factors.

$$Y = f(x_1, \ldots, x_n)$$





L_{12}	N_A	N_B	N_C	N_D	N_E	N_F	N_G	N_H	N_I	N_J	N_K	Y_1	Y_2	…	Y_n
1	1	1	1	1	1	1	1	1	1	1	1				
2	1	1	1	1	1	2	2	2	2	2	2				
3	1	2	2	2	2	1	1	1	2	2	2				
4	1	2	1	2	2	1	2	2	1	1	2				
5	1	1	2	1	2	2	1	2	1	2	1				
6	1	1	2	2	1	2	2	1	2	1	1				
7	2	2	2	2	1	1	2	2	1	2	1				
8	2	2	2	1	2	2	2	1	1	1	2				
9	2	1	1	2	2	2	1	2	2	1	1				
10	2	1	2	1	1	1	1	2	2	1	2				
11	2	2	1	2	1	2	1	1	1	2	2				
12	2	2	1	1	2	1	2	1	2	2	1				

1. Best Practices: Tracking Critical Relationships

Requirement allocation flows down…

Y: System Level Functions

Rqmt

S, C_p

y: Subsystem Level Functions

Rqmt

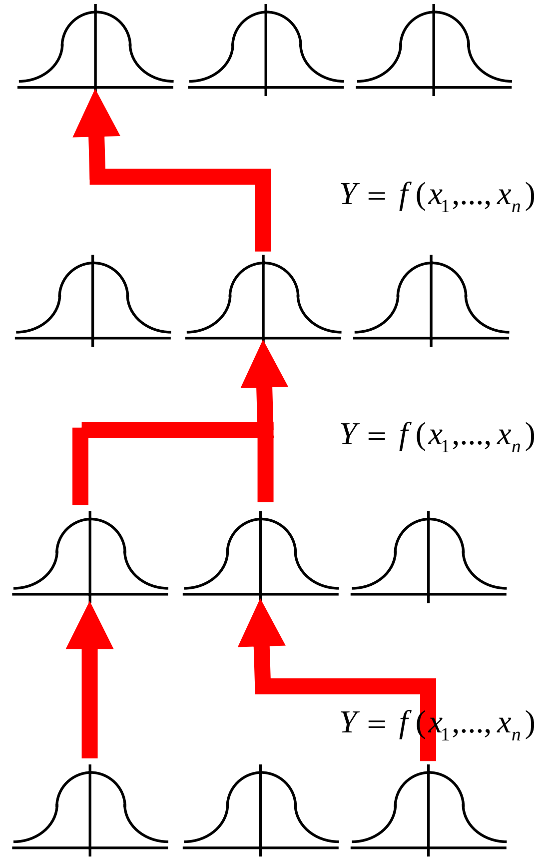
S, C_p

x: Component Level Specs.

Rqmt

S, C_p

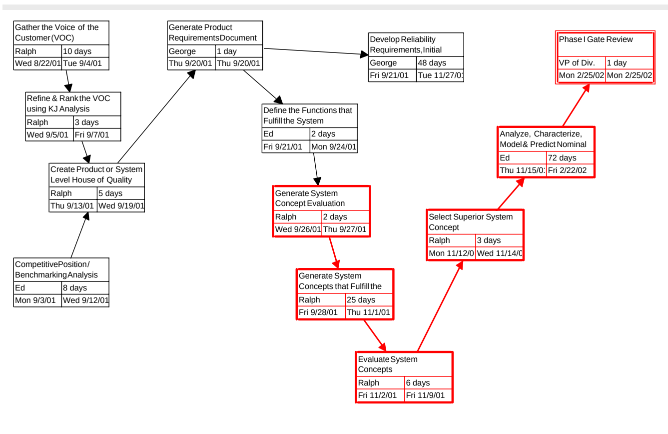
p: Mfg. Process Specs



… build up and verify the variability stackup!

$$C_p = \frac{\text{Reqmt}}{\text{Capability}} = \frac{\text{USL-LSL}}{6s}$$

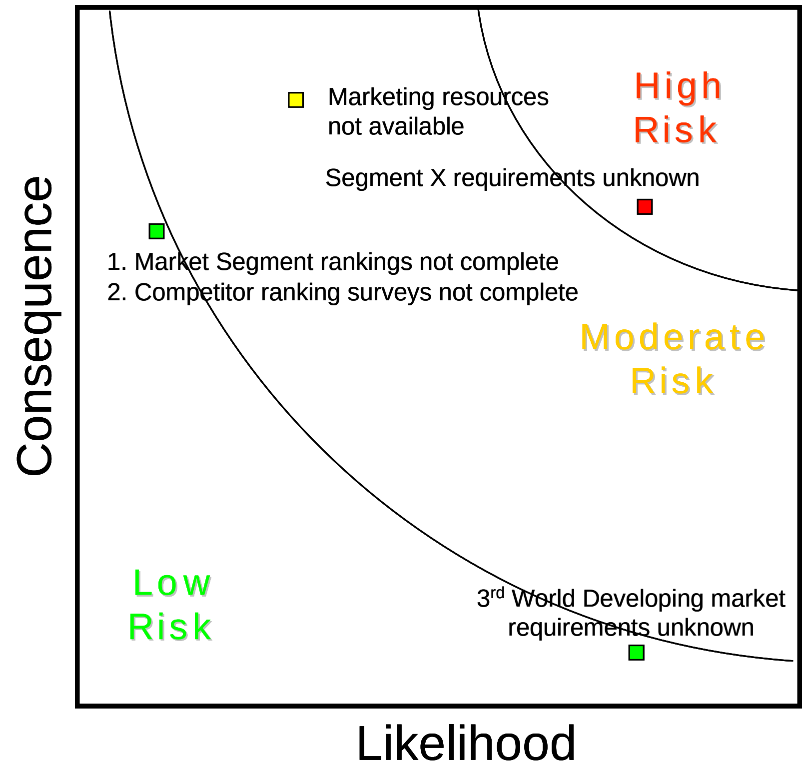
2. Project Management: Where's the risk?



Microsoft Project

Phase Task:	% Task Fulfillment	Task Result vs. D&R Reqts	Red	Yellow	Green	Deliverable Requirements

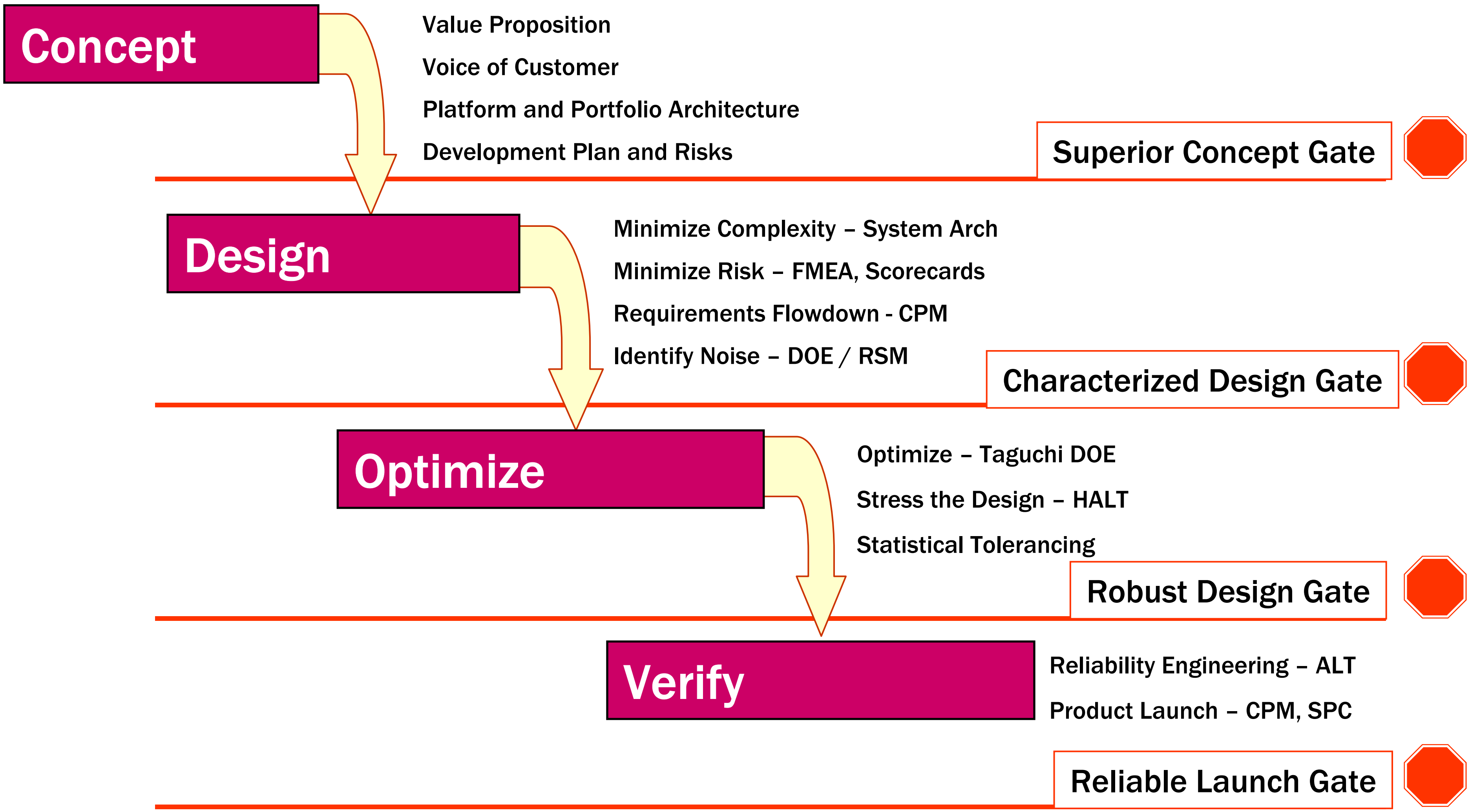
Risk Scorecard for each Task



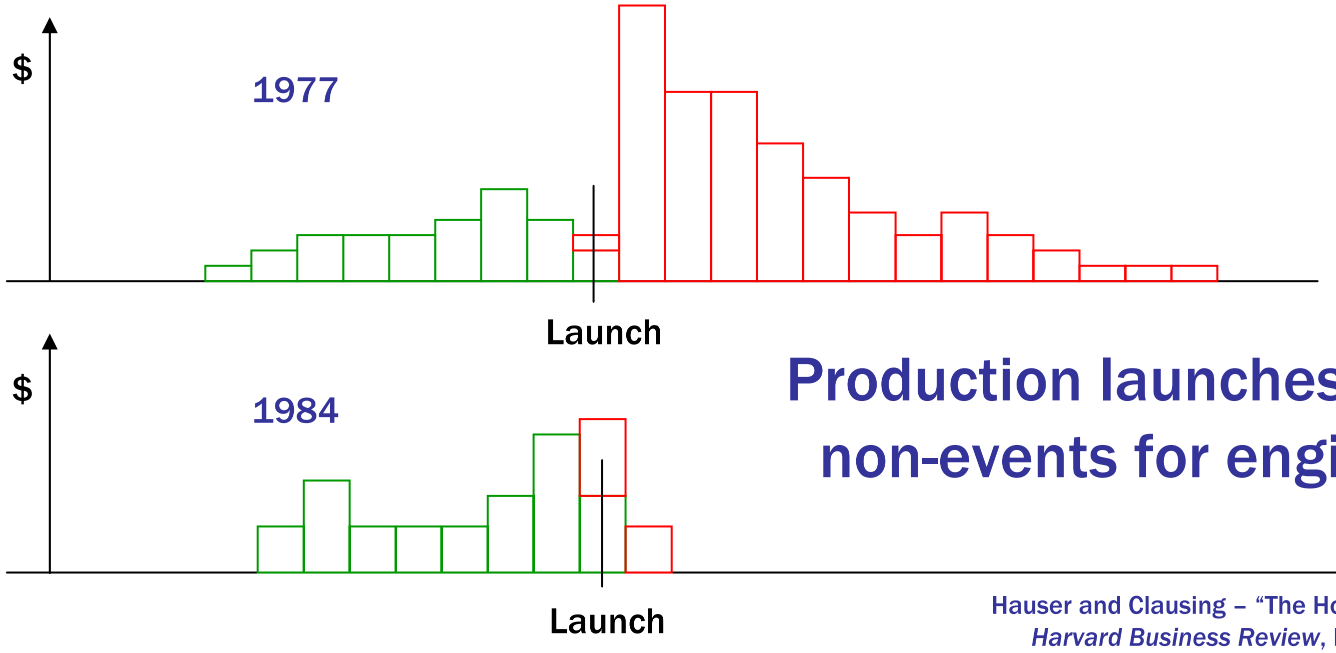
Gate Review: Risk Summary and backup plans

Manage not only time, but risk.

3. Product Development Process – The CDOV Process



Effect of Critical Parameter Management at Toyota



Production launches become non-events for engineering

Hauser and Clausing – "The House of Quality"
Harvard Business Review, May-June 1988

- What will happen when product starts, and there is a problem with a component, assembly step, ...?
  - Off target, Too much variation
  - Acting differently than the development prototypes
- With DFSS, you know what to do $Y = f(x_1, \ldots, x_n)$
  - You have pre-defined factors x to shift every response (Y or y)
  - Factors x that production and design agree to use

SYSTEMS ENGINEERING

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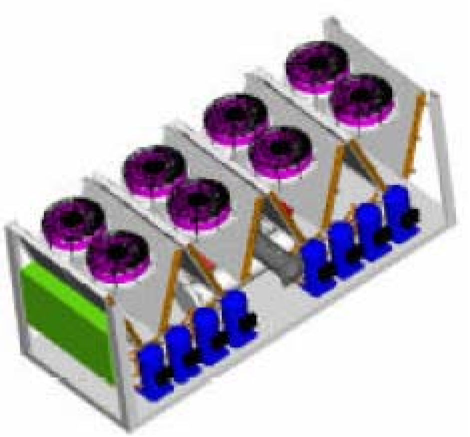
How do you verify modular designs?

- ABB Axial Fans: over 1 billion permutations

- Carrier Chillers: over 800 billion permutations



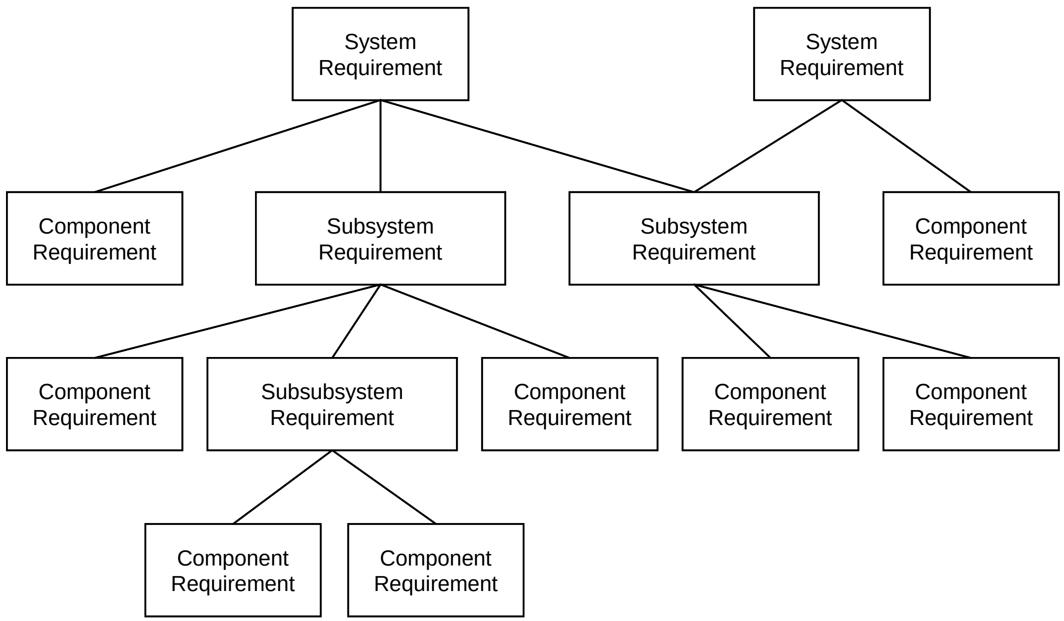
- Imagine you are responsible for launching this.
  Mechanical. Electronics. Software.
  Will all these future builds all work?

Systems Engineering

- Not just a single project launch
- How do you ensure complex engineering systems?
- Multiple disciplines
- Multiple sizes and configurations
- Interactions
- Trade-offs

State of the art: Managed Requirements

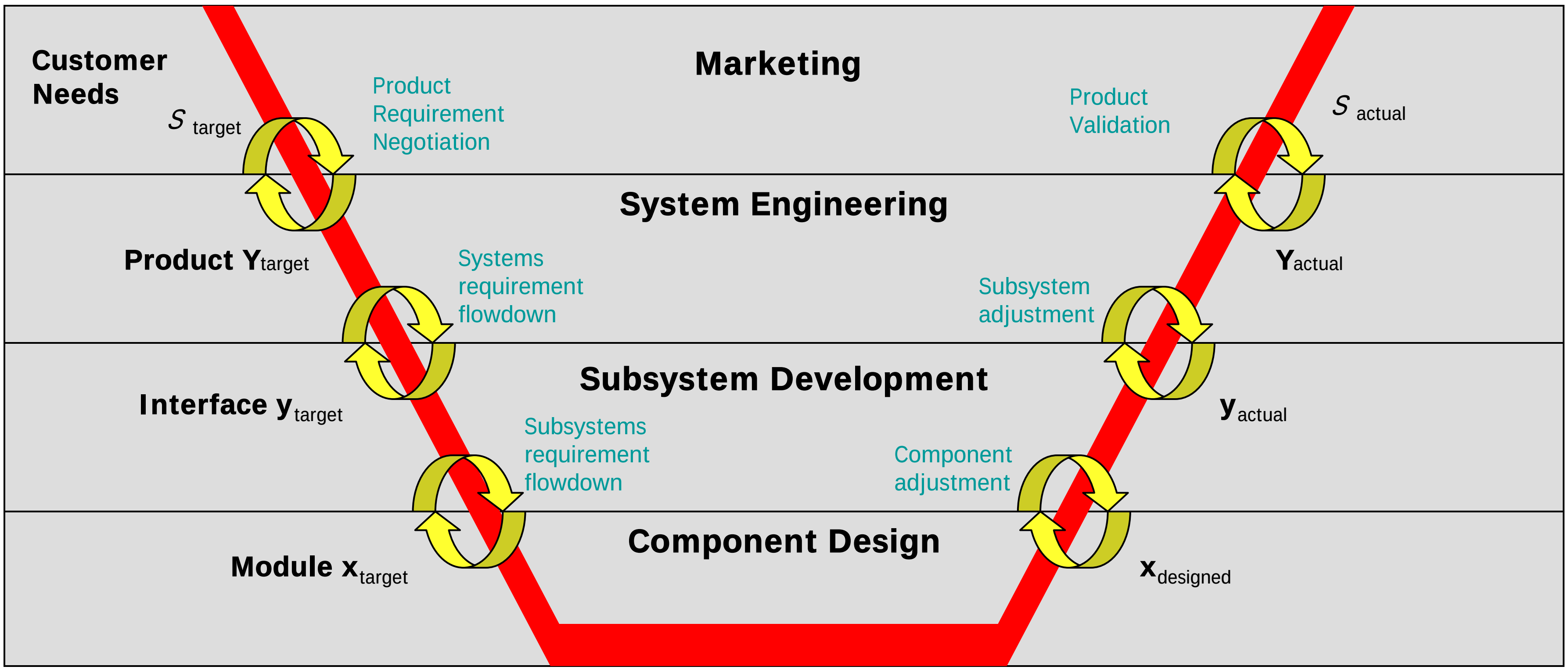
- Requirements documented to show traceability
  - Linked to other requirements that it impacts
  - Usually modeled in DOORS, CORE, etc.



- Not quantified. Only represents causality

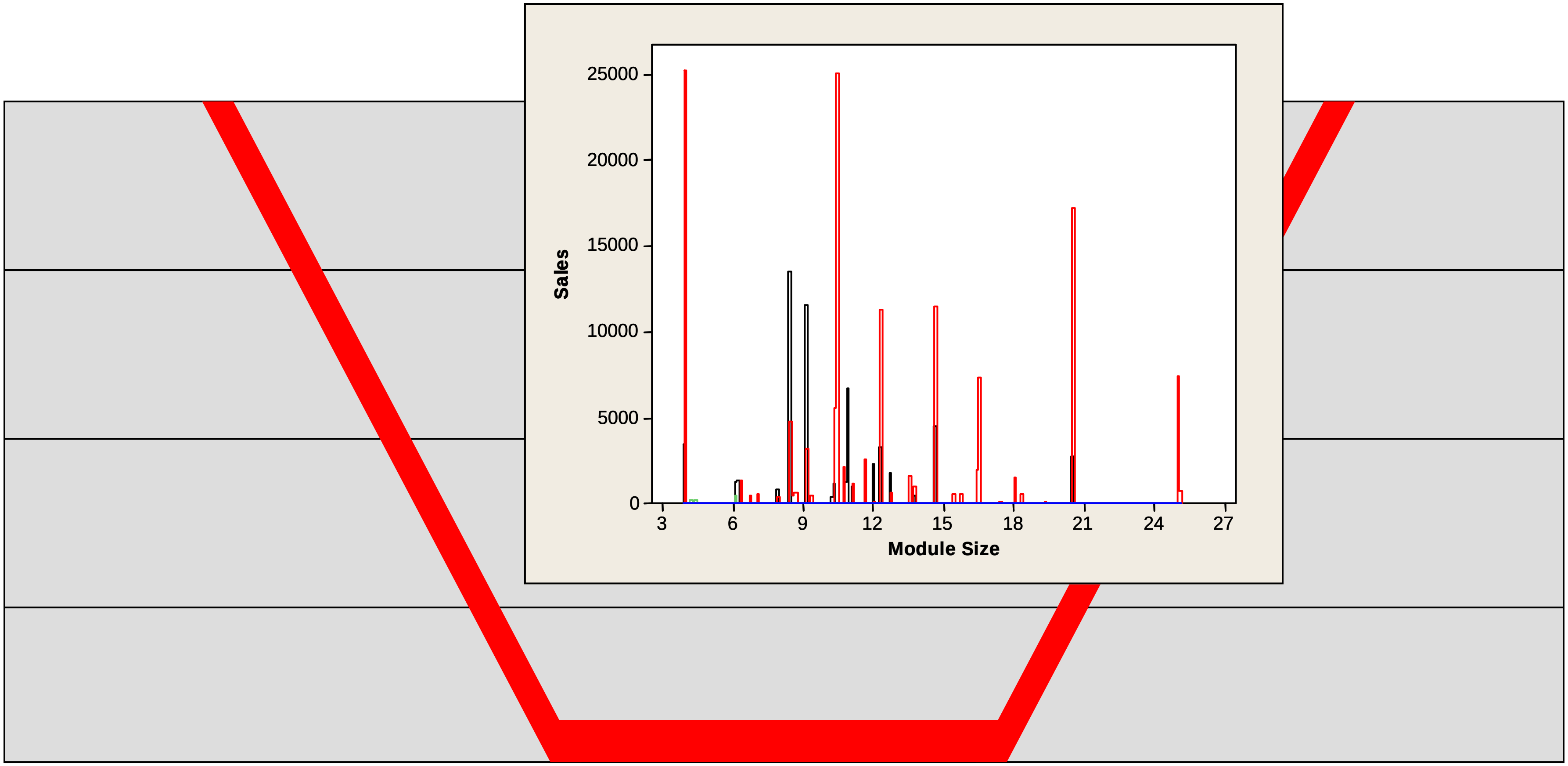
Modern System Engineering

- Flowdown requirements allocation…



- …Build up experimental verification

What happens...



Critical Parameter Management

- Critical: focus on only the critical 10% of all requirements
- Parameter: we will be quantitative, measurable and testable
- Management: we will improve, control, tradeoff with a total systems perspective

Criticality Scorecards

CFR Output Variability

CFR Output (Y)

$$Y = f(x_1, \ldots, x_n)$$

Design For Six Sigma Scorecard

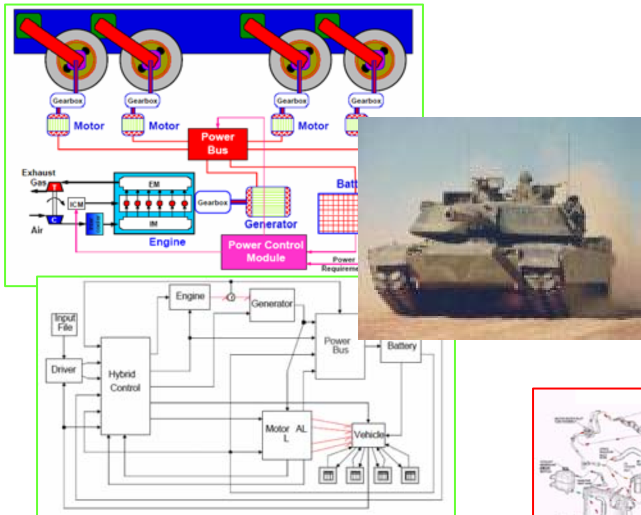
Performance		Transfer Function		Specification			Estimates Based on Mean Condition of x's and n's Listed Below: Predicted Performance Capability				6σ Score		
Characteristic	Units	Y/N	Formula (enter below)	Target	USL	LSL	mean: μ	s.d.: σ	Short/Long	Confidence	z	σ-shift	DPM
Voltage	V	Y	2	2	2.1	1.9	2	0.008654			11.55	0.00	0.0

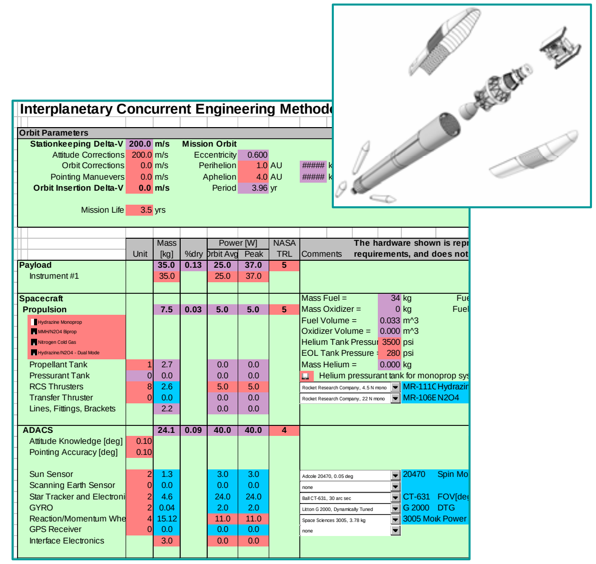
x's, Input Control Factors: Variables			Range		Contribution to Variability		Specification		Sample/Database Statistics				6σ Score		
No	Characteristic	Units	Min	Max	Sensitivity	%	USL	LSL	mean: μ	s.d.: σ	Short/Long	Confidence	z	σ-shift	DPM
1	X1	ohms	20	500	0	0.00%			20	0.04899			-408.25		1000000.0
2	X2	ohms	2	50	-0.3108194	32.03%			6.433029	0.015758			-408.25		1000000.0
3	X3	ohms	2	50	0.4176437	32.04%			4.788771	0.01173			-408.25		1000000.0
4	X4	volts	1.2	30	0	0.00%			30	0.03873			-774.60		1000000.0
5	X5	ohms	2	50	0	0.00%			2	0.004899			-408.25		1000000.0
6	X6	ohms			0.7444038	32.04%			2.686714	0.006581			-408.25		1000000.0
7	I	amp			-10.449776	3.89%			0	0.000163			0.00		933192.8
8															
9															
10															
11															
12															
13															
14															

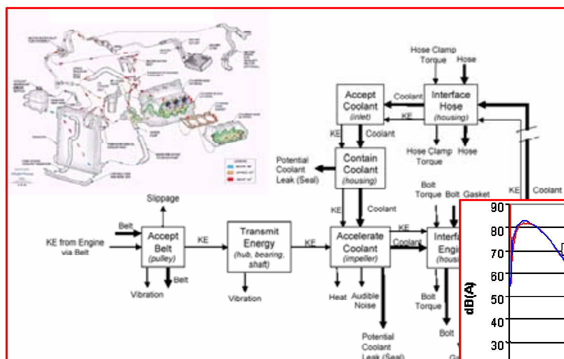
CTS Control factors (x)

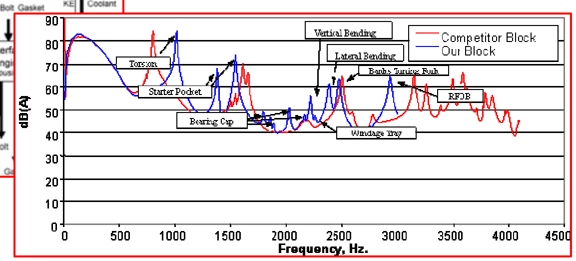
CTS Control factor Variability

Modeling





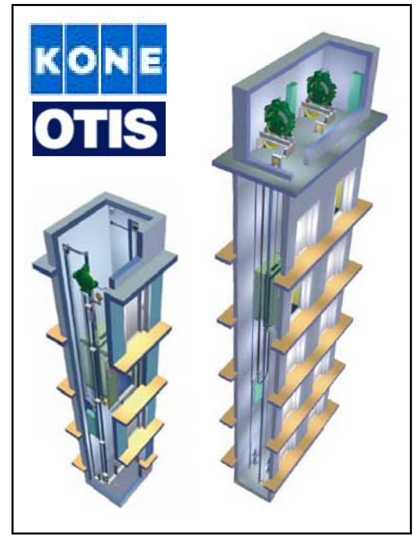


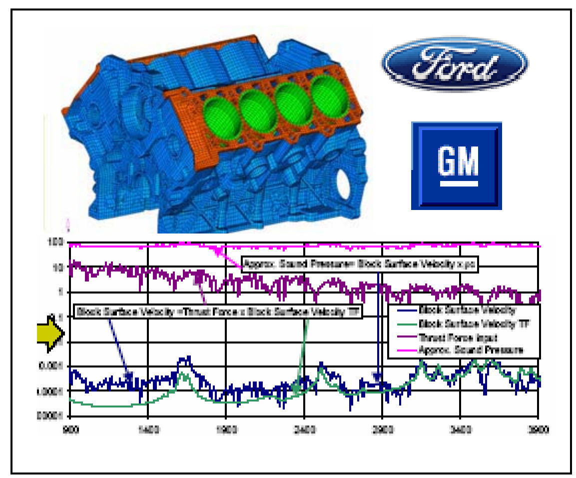


- Typically just used for design
  - Requirements allocation
  - Optimization
- Not trusted for verification

Acoustic Noise Model

Subsystem	Stackup		Sensitivity
Motor	8.14E-07	W (A wt)	-0.7 dBA
Supports	2.55E-06	W (A wt)	-0.2 dBA
Transmission	3.05E-05	W (A wt)	-1.6 dBA
Frame	3.67E-07	W (A wt)	-1.3 dBA
Cab	1.31E-08	W (A wt)	-2.0 dBA
Doors	4.84E-09	W (A wt)	-0.6 dBA
In-Car	**50.6**	dBA	





How accurate is the model?

- In product development, we use models to provide information about new designs

- Our model accuracy can only be assessed against applications of the model
  - Past product launches
  - Competitive products we have torn down

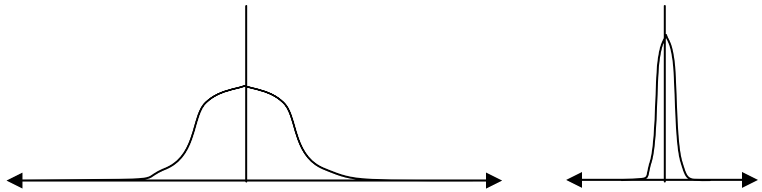
Previous Model Applications

Over the past 12 uses of the model, the following accuracies were experienced

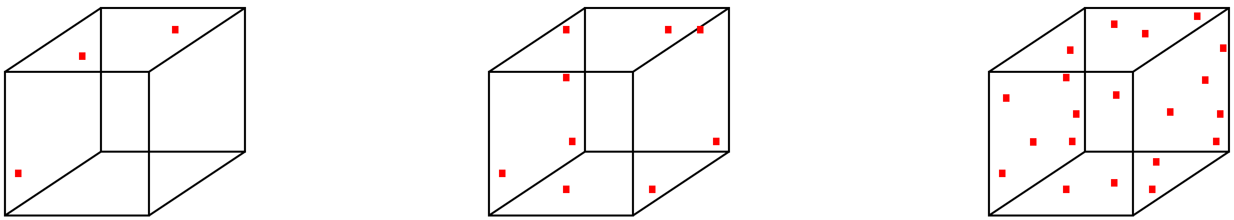
Design	Model	Actual	Error	Variance
A1	50.6	47.8	2.8	7.8
A2	45.5	47.7	-2.2	4.8
B	52.8	56.2	-3.4	11.6
C	55.5	54.9	0.6	0.4
D	67.9	63.9	4.0	16.0
E1	42.0	47.5	-5.5	30.0
E2	57.0	56.0	1.0	1.0
E3	46.0	48.2	-2.2	4.8
F	46.3	48.1	-1.8	3.2
G1	51.2	52.6	-1.4	2.0
G2	48.3	45.3	3.0	9.0
G3	57.6	55.0	2.6	6.8
		RMS Model Error	**±2.8**	
		% Error	**±6%**	

Statistics!

- **A model's accuracy *can* be characterized based upon past uses**
- **Two factors to consider**
  - **Confidence: how far are the predictions from the measurements?** $\pm\varepsilon$ (accuracy)

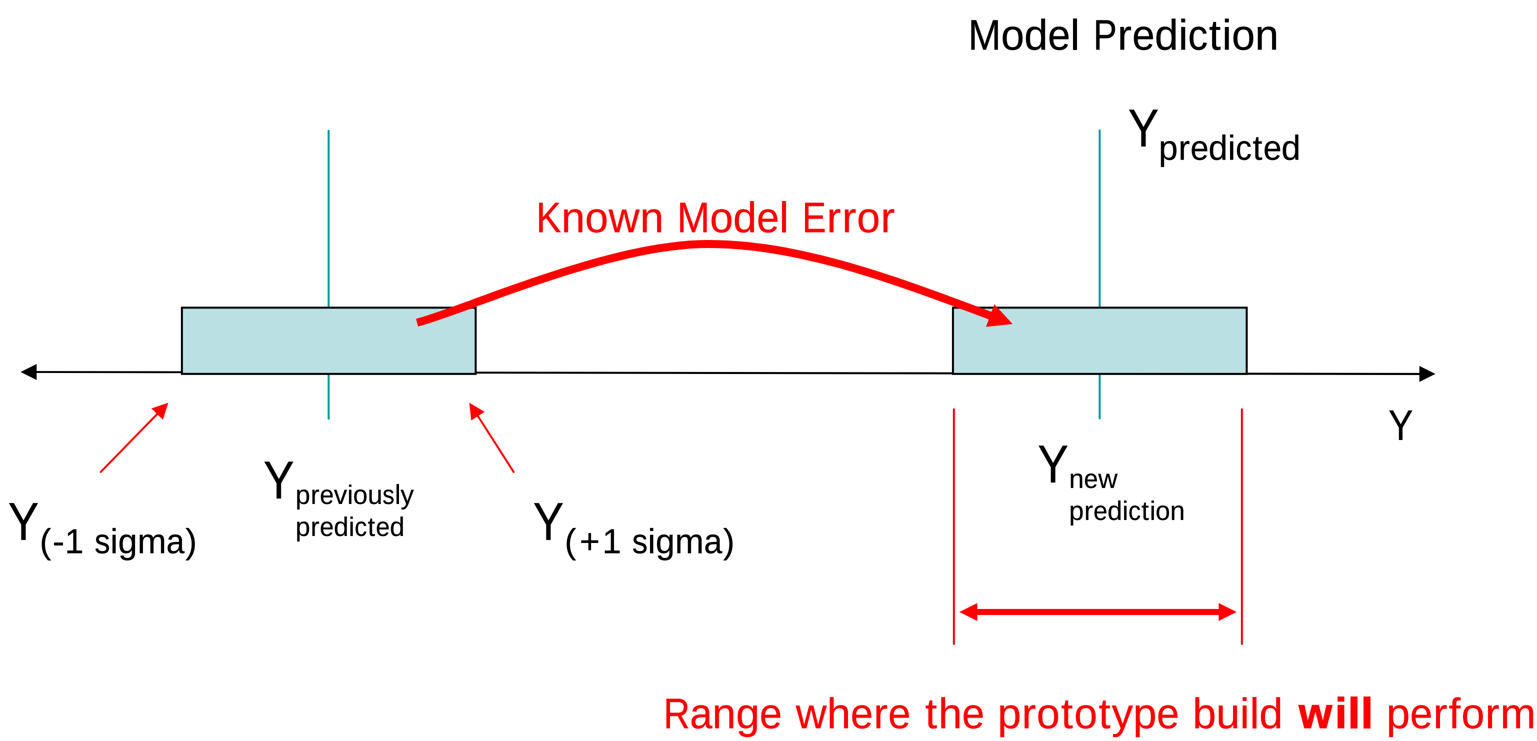


  - **Power: is there a sufficient set of tests (domain) for the accuracy characterization to be applicable?**



Design Span and Model Error

Past Designs... ...Future Build



What does this mean for the requirement flowdown?

Subsystem	Stackup	Sensitivity
Motor	8.14E-07 W (A wt)	-0.7 dBA
Supports	2.55E-06 W (A wt)	-0.2 dBA
Transmission	3.05E-05 W (A wt)	-1.6 dBA
Frame	3.67E-07 W (A wt)	-1.3 dBA
Cab	1.31E-08 W (A wt)	-2.0 dBA
Doors	4.84E-09 W (A wt)	-0.6 dBA
In-Car	**50.6** dBA	

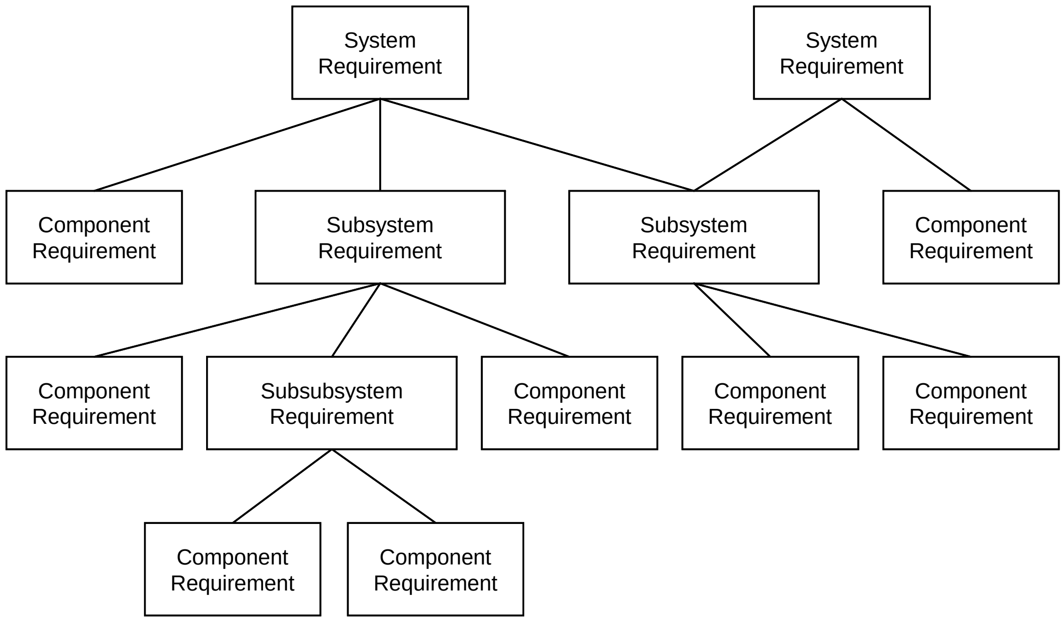
Model Error

± **2.8** TOTAL MODEL VARIANCE (dBA)

± **6%** TOTAL MODEL % VARIANCE

Now Cascade the Error!

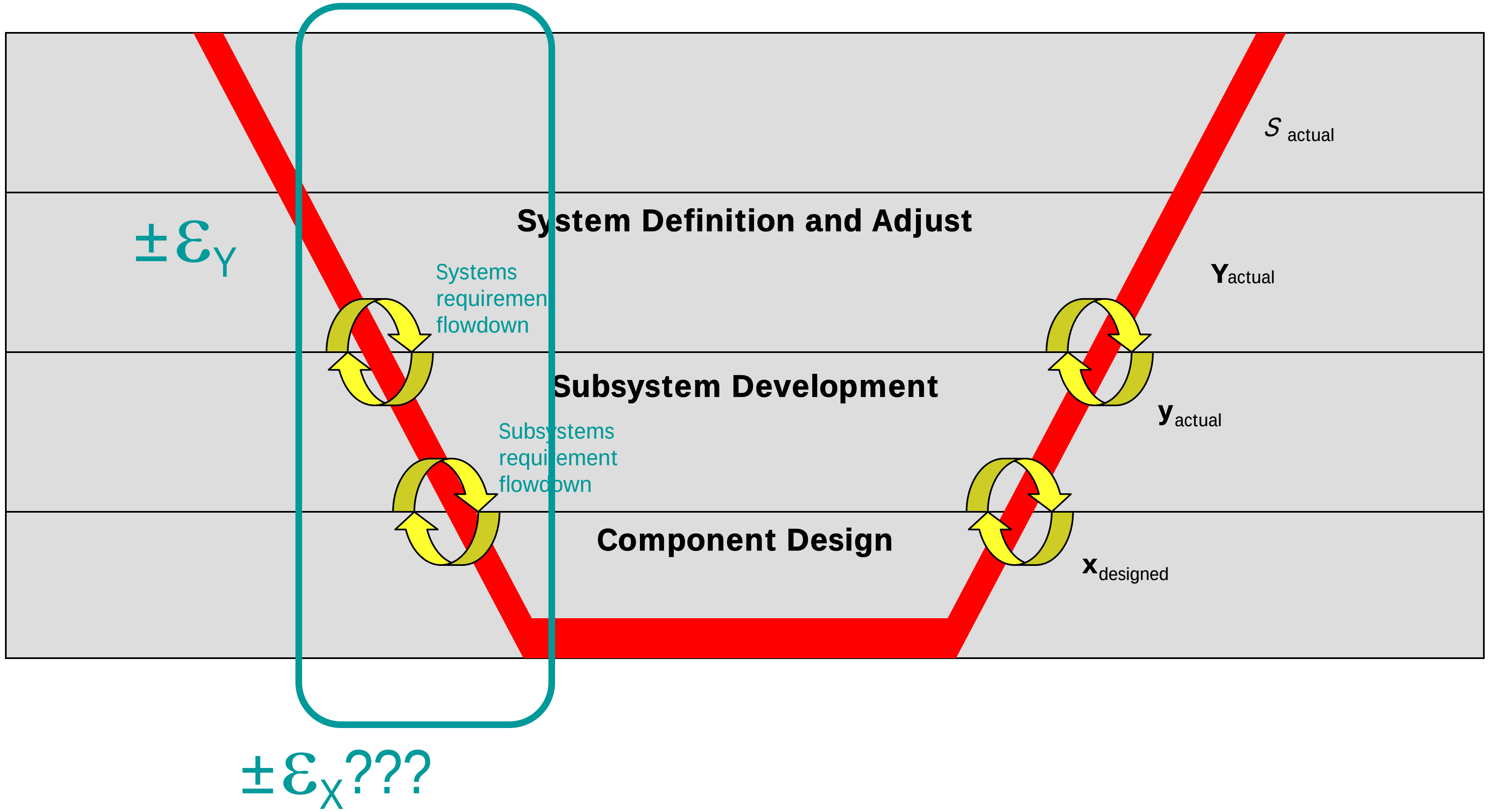
- What are you going to do about that error?



- You have a model…
- You know the ± error on Y…
- …So calculate ± range on X’s!

Target Cascading

- Use to cascade targets and plan for variation



Subsystem Concept Phase Efforts

- Design the nominal system (Design A) — Y
  - One that meets requirements on paper
- Design a "backup-plan" system (Design B) — $Y \pm \varepsilon$
  - One that meets requirements ± the model error

Every subsystem team must create these *two* designs.

Pre-Calculate Your Future Iteration!

- Design a system with target = (nominal – sigma)

Subsystem	Stackup		Sensitivity	Risk Backup Plan	
Motor	8.14E-07	W (A wt)	-0.7 dBA	8.14E-07	W (A wt)
Supports	2.55E-06	W (A wt)	-0.2 dBA	2.55E-06	W (A wt)
Transmission	3.05E-05	W (A wt)	-1.6 dBA	1.52E-05	W (A wt)
Frame	3.67E-07	W (A wt)	-1.3 dBA	1.07E-07	W (A wt)
Cab	1.31E-08	W (A wt)	-2.0 dBA	1.18E-08	W (A wt)
Doors	4.84E-09	W (A wt)	-0.6 dBA	2.13E-09	W (A wt)
In-Car	**50.6**	dBA		**47.6**	dBA

Nominal Design A

Model Error
± **2.8** TOTAL MODEL VARIANCE (dBA)
± **6%** TOTAL MODEL % VARIANCE

Backup Design B

The "Math"...

- We choose two designs A and B such that they cover the model error ε. Since

$$\left| y_{\mathrm{A}} - y_{\mathrm{B}} \right| = \varepsilon$$

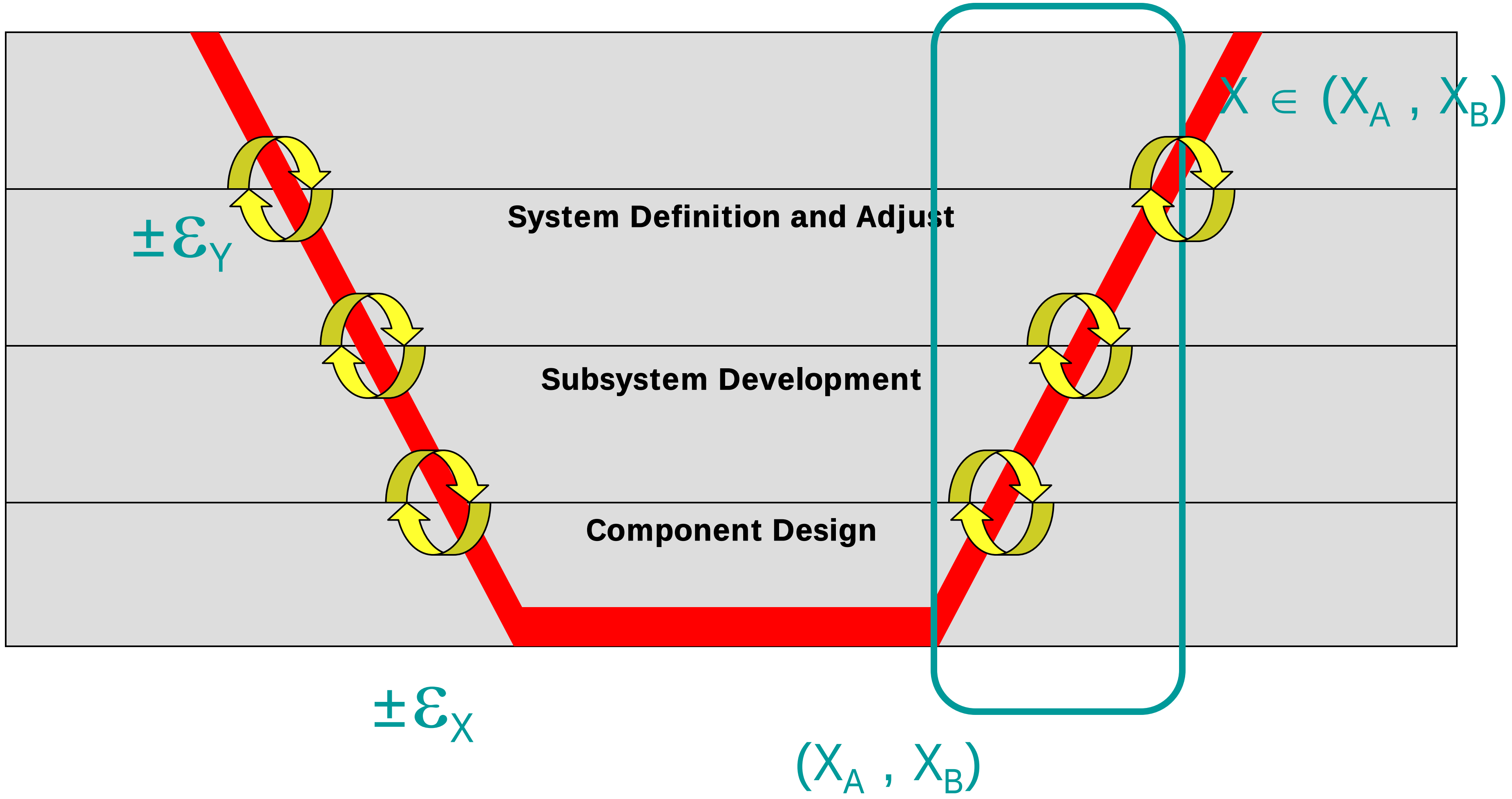
- Then the future design changes in the prototype *will be* scoped within

$$\vec{x}_{\mathrm{A}} \leq \vec{x}_{\substack{\text{rebalanced} \\ \text{prototype}}} \leq \vec{x}_{\mathrm{B}}$$

with probability 68% (±1 sigma).

System Integration

- Use models to eliminate prototype iterations



This works…

- In my experience, this easily cuts verification time in half
- In my experience, this improves reliability and robustness
  - Do not rely on fixes or service procedures
  - Design in capability

How do you do this with Modular Platforms?

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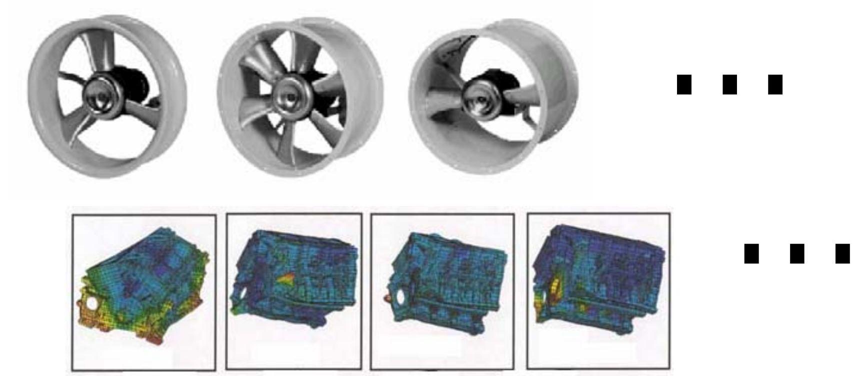
Issue: Modules are Used in Many Different Product Configurations

- Which module configurations do you analyze?
- Which do you build to verify the model?
- Which do you use to define the range of X?
- When do you do what?

Which module combinations do you analyze?

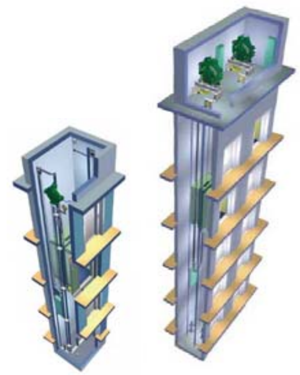
- Virtually build and analyze ***all*** of them!



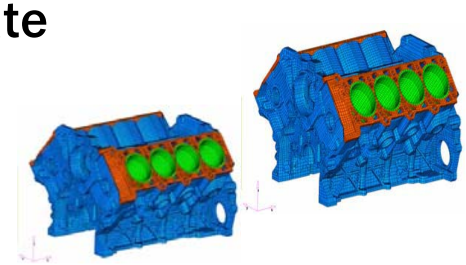
- Computing is cheap
- Build the IT infrastructure to batch job the virtual simulation of every module combination as you make design changes

Which do you verify with Hardware?

- *The corner cases of performance*…



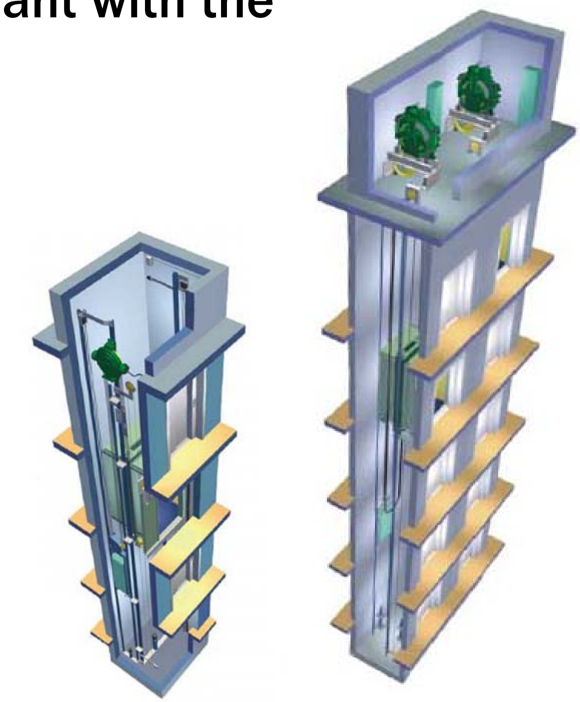
- For each Y, using your model calculate
  - System configurations X: requirement Y is max and min
- For each module, using your model calculate
  - System configurations X: interface y is max and min



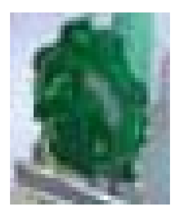
- Build this smaller set of modules for prototyping
- Assemble the corner combinations
- Be prepared to build each module configuration X to ± the widest model error range of all Y and y

Limits of Performance

- Use your model to calculate the product variant with the maximum/minimum of Y

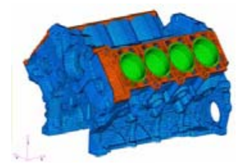


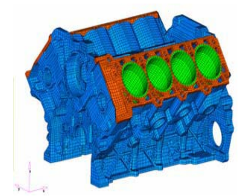
- Build these configurations
- Propagate your model error $\pm\varepsilon_Y$ onto the design X as before
  - Define Systems (X_A, X_B)
  - This defines modules (x_A, x_B)



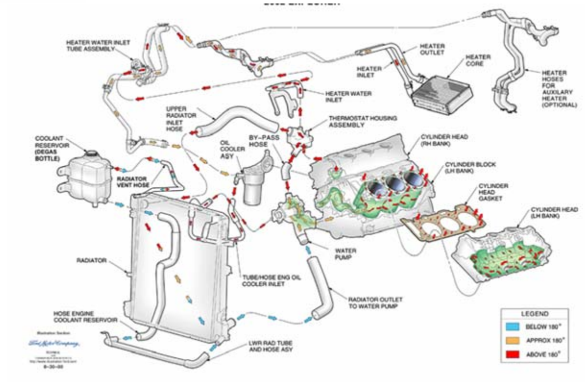
Corner Cases of Module Requirements

- Use your model to calculate the module variants with the maximum/minimum of the module requirements y



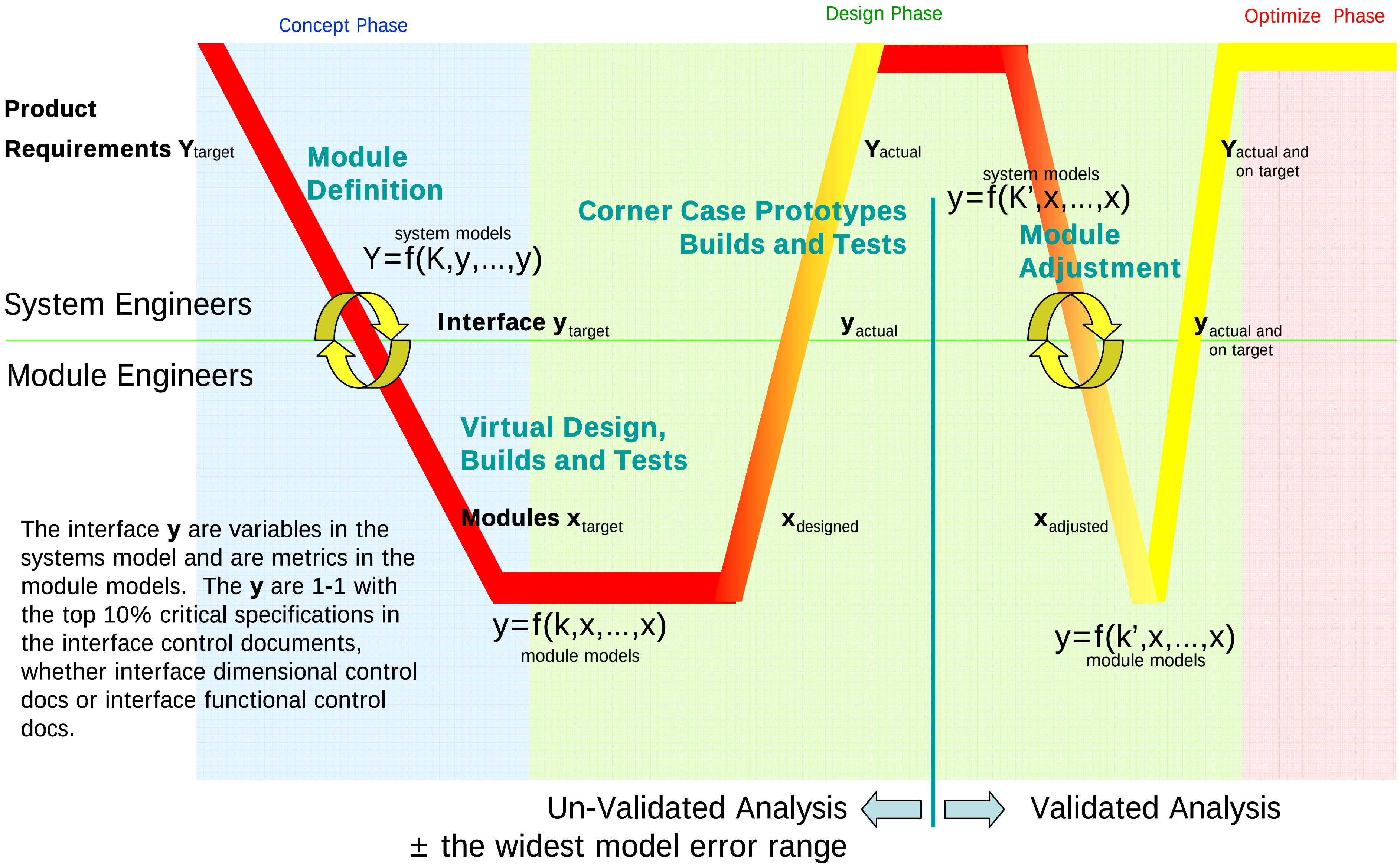


- Build these modules
- Assemble them into the system configurations per the model



- Propagate your model error $\pm\varepsilon_y$ onto the module designs x as before
  - Defines modules (x_A, x_B)
  - This defines systems (X_A, X_B)

Modular Systems Design and Models



The interface **y** are variables in the systems model and are metrics in the module models. The **y** are 1-1 with the top 10% critical specifications in the interface control documents, whether interface dimensional control docs or interface functional control docs.

This works…

- Cuts verification time in half
- Enables modularity of mechanical systems
  - Assurance the module will work across variants
  - Even the worst case applications
  - Even with interfaces carrying power
- Improves reliability and robustness
  - Do not rely on fixes or service procedures
  - Design in capability

Problems You Will Encounter

- Lack of executive support
- Yet another program of the month
- We already do this
- We don't need to do this
- Hired external design firms are incapable

Success Factors

- Executive champion
  - One who believes and is staking their job on DFSS success
  - Clears obstacles faced by project champion
- Project Manager
  - One who believes and is staking their job on DFSS success
  - Person skills: can attain buy-in from support functions
- DFSS Master Black Belt
  - Training and consulting, reports to Executive and PM
  - Responsible for launch quality and lifetime reliability
  - Ensure effective tool use
- Modeling Manager hip-to-hip with Project Manager
- Defined Development Process
- Test facilities, Field data collection, Supply chain support

QUESTIONS?

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