How to Improve the Effectiveness, Efficiency, and Integration of Test & Evaluation (T&E) and Modeling and Simulation (M&S)

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Agenda

- Some Basic Definitions
- The Heart and Soul of Multivariate Testing
- Integrating T&E with M&S
- Examples of Iterative Use of Modeling and Simulation
- Summary of “Modeling the Simulator”

Some Basic Definitions

- **System:** a collection of entities which act and interact together to achieve some goal

- **Model:** a simplified representation of a system developed for the purpose of studying a system

- **Simulation:** the manipulation of a model in such a way that it allows the investigation of the performance of a system.

- **Modeling and Simulation:** a discipline for developing a level of understanding of the interaction of the parts of a system, and of the system as a whole

About Models

All models are simplifications of reality.

There is always a tradeoff as to what level of detail should be included in the model:

If too little detail, there is a risk of missing relevant interactions and the resultant model does not promote understanding

If too much detail, there is a risk of overly complicating the model and actually preclude the development of understanding

The goodness of a model depends on the extent to which it promotes understanding

Types of Models

High-Fidelity Models:

- many variables and many interactions
- highly detailed and complex
- needed for visualization
- difficult to manipulate

Low-Fidelity Models:

- much fewer number of variables
- can be manipulated more easily
- provides higher-level view of system
- presents a more aggregate view of the system

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Types of Simulation

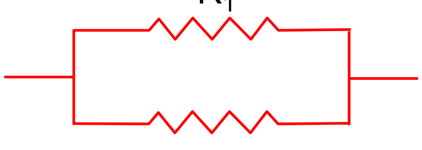
Deterministic Simulation:
- for each combination of inputs parameters, there is one and only one output value
- y = f(x)

Monte Carlo Simulation:
- provides for variability in the inputs
- y = f(x + variation), where the variation is modeled as some probability distribution

Discrete Event Simulation:
- studies a sequence of countable events
- assumption is that nothing of importance takes place between events

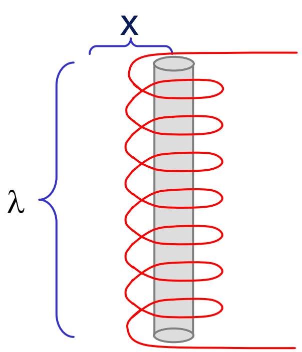
Examples of Low Fidelity Models (Transfer Functions)

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



The equation for the impedance (Z) through this circuit is defined by:

$$Z = \frac{R_1 \cdot R_2}{R_1 + R_2}$$



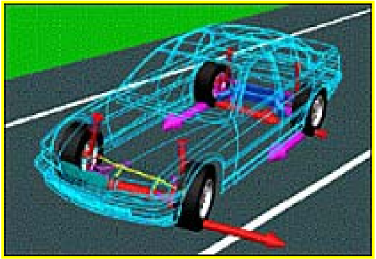
The equation for magnetic force at a distance X from the center of a solenoid is:

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

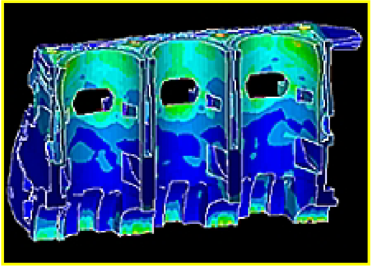
Where
- N: total number of turns of wire in the solenoid
- I: current in the wire, in amperes
- r: radius of helix (solenoid), in cm
- λ: length of the helix (solenoid), in cm
- x: distance from center of helix (solenoid), in cm
- H: magnetizing force, in amperes per centimeter

Examples of High Fidelity Simulation Models

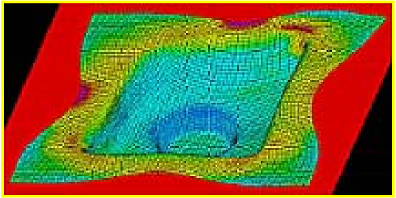
Mechanical motion: **Multibody kinetics and dynamics**
- ADAMS®
- DADS



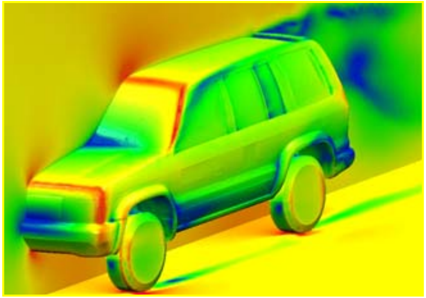
Implicit Finite Element Analysis: **Linear and nonlinear statics, dynamic response**
- MSC.Nastran™, MSC.Marc™
- ANSYS®
- Pro MECHANICA
- ABAQUS® Standard and Explicit
- ADINA



Explicit Finite Element Analysis : **Impact simulation, metal forming**
- LS-DYNA
- RADIOSS
- PAM-CRASH®, PAM-STAMP



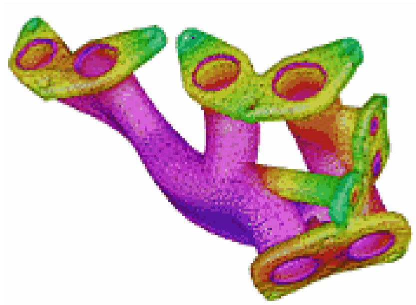
General Computational Fluid Dynamics: **Internal and external flow simulation**
- STAR-CD
- CFX-4, CFX-5
- FLUENT®, FIDAP™
- PowerFLOW®



Examples of High Fidelity Simulation Models

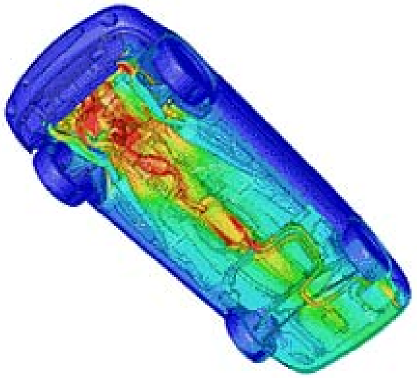
Preprocessing: Finite Element Analysis and Computational Fluid Dynamics mesh generation

- ICEM-CFD
- Gridgen
- Altair® HyperMesh®
- I-deas®
- MSC.Patran
- TrueGrid®
- GridPro
- FEMB
- ANSA



Postprocessing: Finite Element Analysis and Computational Fluid Dynamics results visualization

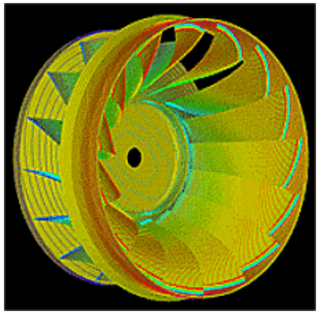
- Altair® HyperMesh®
- I-deas
- MSC.Patran
- FEMB
- EnSight
- FIELDVIEW
- ICEM CFD Visual3 2.0 (PVS)
- COVISE



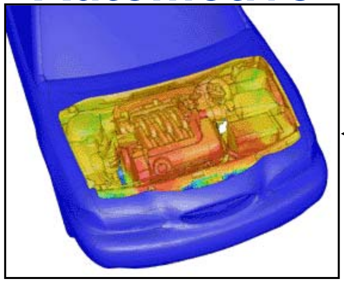
Applications of Modeling and Simulation

Power

Simulation of stress and vibrations of turbine assembly for use in nuclear power generation →



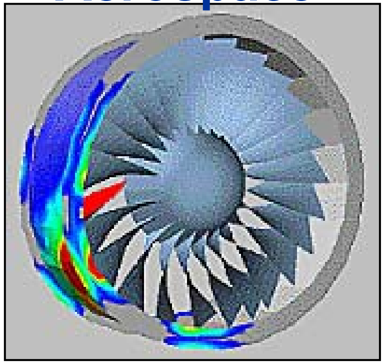
Automotive



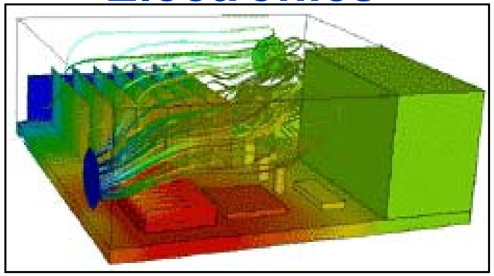
← Simulation of underhood thermal cooling for decrease in engine space and increase in cabin space and comfort

Aerospace

Evaluation of dual bird-strike on aircraft engine nacelle for turbine blade containment studies →



Electronics



← Evaluation of cooling air flow behavior inside a computer system chassis

Reasons for Test & Evaluation

Functional Compatibility:

- to determine if various components or subassemblies work together

Screening:

- to separate the critical parameters from those that are not critical with regard to functionality or performance capability

Modeling:

- to build prediction capability of the performance measures and perform sensitivity and interaction analyses on the critical parameters

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 n-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, IT (see IT example on next page)

HTT Example

- An IT function in a company wanted to test all 2-way combinations of a variety of computer configuration-related options or levels to see if they would function properly together.
- Here are the factors with each of their options:

Motherboards (5)	:	Gateway, ASUS, Micronics, Dell, Compaq
RAM (3)	:	128 MB, 256 MB, 512 MB
BIOS (3)	:	Dell, Award, Generic
CD (3)	:	Generic, Teac, Sony
Monitor (5)	:	Viewsonic, Sony, KDS, NEC, Generic
Printer (3)	:	HP, Lexmark, Cannon
Voltage (2)	:	220, 110
Resolution (2)	:	800x600, 1024x768

- How many total combinations are there?
- What is the minimum number of these combinations we will have to test (and which ones are they) in order to determine if every 2-way combination (e.g., Dell Bios with Teac CD) will indeed work properly together?
- To answer this question, we used Pro-Test software. The answer is 25 runs and those 25 combinations are shown on the next page.

High Throughput Testing (HTT)

(for all two-way combinations)

Full Factorial = 8100 runs HTT = 25 runs

	5 Levels	*3 Levels*	*3 Levels*	*3 Levels*	*5 Levels*	*3 Levels*	*2 Levels*	*2 Levels*
	Motherboard	**RAM**	**BIOS**	**CD**	**Monitor**	**Printer**	**Voltage**	**Resolution**
Case 1	ASUS	256 MB	Dell	Generic	Viewsonic	Lexmark	110 V	800 x 600
Case 2	Compaq	512 MB	Dell	Teac	Sony	HP	220 V	1024 x 768
Case 3	Gateway	128 MB	Generic	Sony	KDS	Cannon	220 V	800 x 600
Case 4	Dell	128 MB	Award	Teac	NEC	Cannon	110 V	1024 x 768
Case 5	Micronics	256 MB	Generic	Teac	Generic	Lexmark	220 V	1024 x 768
Case 6	Gateway	256 MB	Award	Sony	Sony	HP	110 V	1024 x 768
Case 7	Micronics	512 MB	Award	Generic	Viewsonic	Cannon	220 V	1024 x 768
Case 8	ASUS	512 MB	Generic	Teac	KDS	HP	220 V	1024 x 768
Case 9	Compaq	128 MB	Award	Generic	Generic	HP	110 V	800 x 600
Case 10	Micronics	512 MB	Generic	Teac	Sony	Lexmark	110 V	800 x 600
Case 11	Dell	256 MB	Award	Generic	KDS	Lexmark	110 V	1024 x 768
Case 12	Gateway	512 MB	Dell	Sony	Generic	Lexmark	110 V	1024 x 768
Case 13	Compaq	256 MB	Generic	Sony	Viewsonic	Cannon	220 V	1024 x 768
Case 14	ASUS	128 MB	Dell	Sony	NEC	Cannon	220 V	800 x 600
Case 15	Micronics	128 MB	Dell	Sony	KDS	Lexmark	220 V	800 x 600
Case 16	Gateway	128 MB	Generic	Teac	Viewsonic	HP	110 V	800 x 600
Case 17	Dell	128 MB	Dell	Sony	Sony	Cannon	110 V	1024 x 768
Case 18	ASUS	256 MB	Award	Sony	Generic	Cannon	220 V	1024 x 768
Case 19	Compaq	512 MB	Dell	Sony	NEC	Lexmark	110 V	800 x 600
Case 20	Gateway	256 MB	Generic	Generic	NEC	Cannon	220 V	800 x 600
Case 21	Micronics	512 MB	Generic	Teac	NEC	HP	220 V	800 x 600
Case 22	ASUS	256 MB	Generic	Generic	Sony	HP	110 V	800 x 600
Case 23	Dell	512 MB	Generic	Sony	Viewsonic	HP	220 V	1024 x 768
Case 24	Compaq	256 MB	Dell	Generic	KDS	Cannon	220 V	1024 x 768
Case 25	Dell	128 MB	Generic	Sony	Generic	HP	110 V	800 x 600

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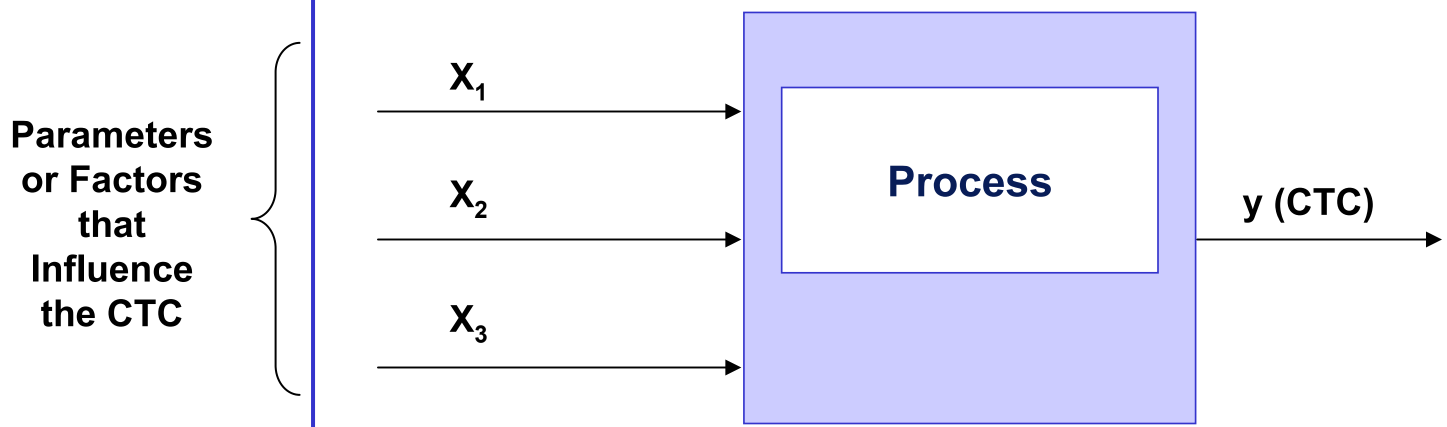
Test and Evaluation for Screening and Modeling



$$\hat{y} = f_1(x_1, x_2, x_3)$$

$$\hat{s} = f_2(x_1, x_2, x_3)$$

Where does the data for evaluation come from?

- Design of Experiments (Multivariate Testing)
- Historical Data Analysis
- Simulation

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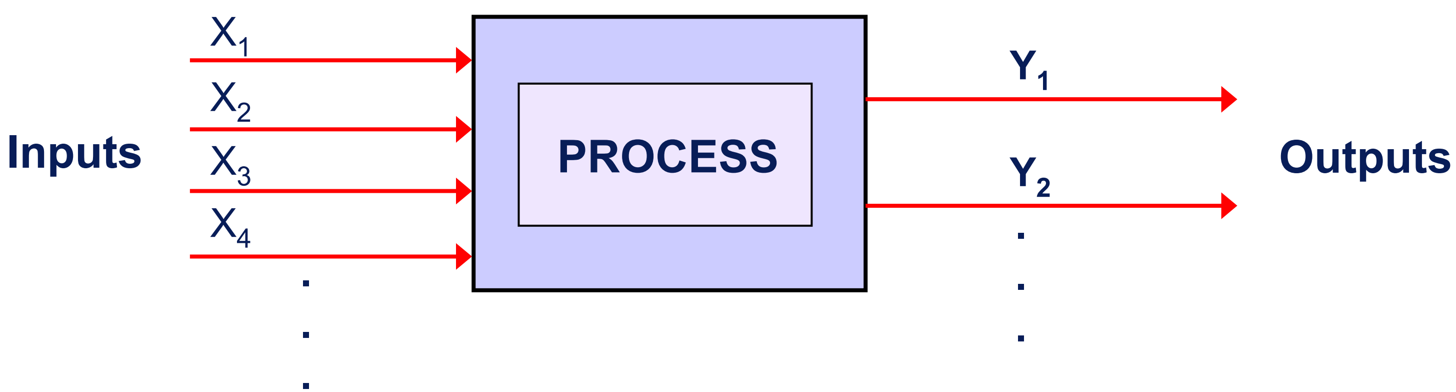
Design of Experiments (DOE)

- An optimal data collection methodology
- “Interrogates” the process
- Used to identify important relationships between input and output factors
- Identifies important interactions between process variables
- Can be used to optimize a process
- Changes “I think” to “I know”

What Is a Designed Experiment?

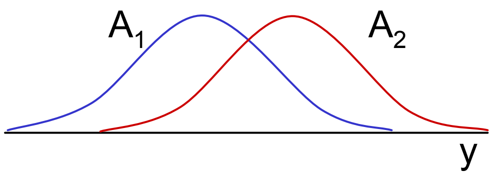
Purposeful changes of the inputs (factors) in order to observe corresponding changes in the output (response).



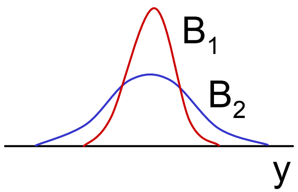
Run	X_1	X_2	X_3	X_4	Y_1	Y_2	. . . . . .	$\bar{Y}$	S_Y
1									
2									
3									
.									
.									

DOE: Determining How Inputs Affect Outputs

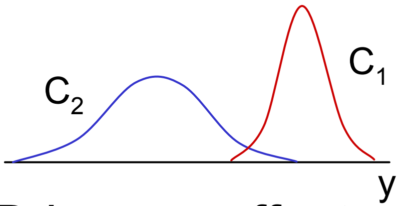
i) Factor A affects the average



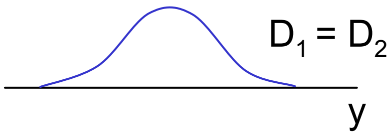
ii) Factor B affects the standard deviation



iii) Factor C affects the average and the standard deviation



iv) Factor D has no effect



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Today's Methods of Experimentation: Orthogonal or Nearly Orthogonal Designs

- FULL FACTORIALS (for small numbers of factors)
- FRACTIONAL FACTORIALS
- PLACKETT - BURMAN
- LATIN SQUARES
- HADAMARD MATRICES
- BOX - BEHNKEN DESIGNS
- CENTRAL COMPOSITE DESIGNS

} Taguchi Designs (PLACKETT - BURMAN, LATIN SQUARES, HADAMARD MATRICES)

SIMPLE DEFINITION OF TWO-LEVEL ORTHOGONAL DESIGNS

Run	Actual Settings	Coded Matrix	Response
1			
2			
3			
4			
5			
6			
7			
8			

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DOE "Market Research" Example

Purpose:

1. Determine the relative importance of product attributes in the consumer choice process
2. Determine the composition of the most preferred product
3. Estimate market share of a given product
4. Segment the market as to their preferred product profile

DOE "Market Research" Example (cont.)

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:	$-1 \leq 2$ people	0 = 3-5 people	$+1 \geq 6$ people
G: Gas Mileage:	$-1 \leq 20$ mpg	0 = 20-30 mpg	$+1 \geq 30$ mpg
H: Price:	$-1 \leq \$20$K	0 = $20-$40K	$+1 \geq \$40$K

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

J: Age:	$-1 \leq 25$ years old	$+1 \geq 35$ years old
K: Income:	$-1 \leq \$30$K	$+1 \geq \$40$K
L: Education:	-1 < BS	$+1 \geq$ BS

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:

									L	-	+	-	+	-	+	-	+		
									K	-	-	+	+	-	-	+	+		
									J	-	-	-	-	+	+	+	+		
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
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

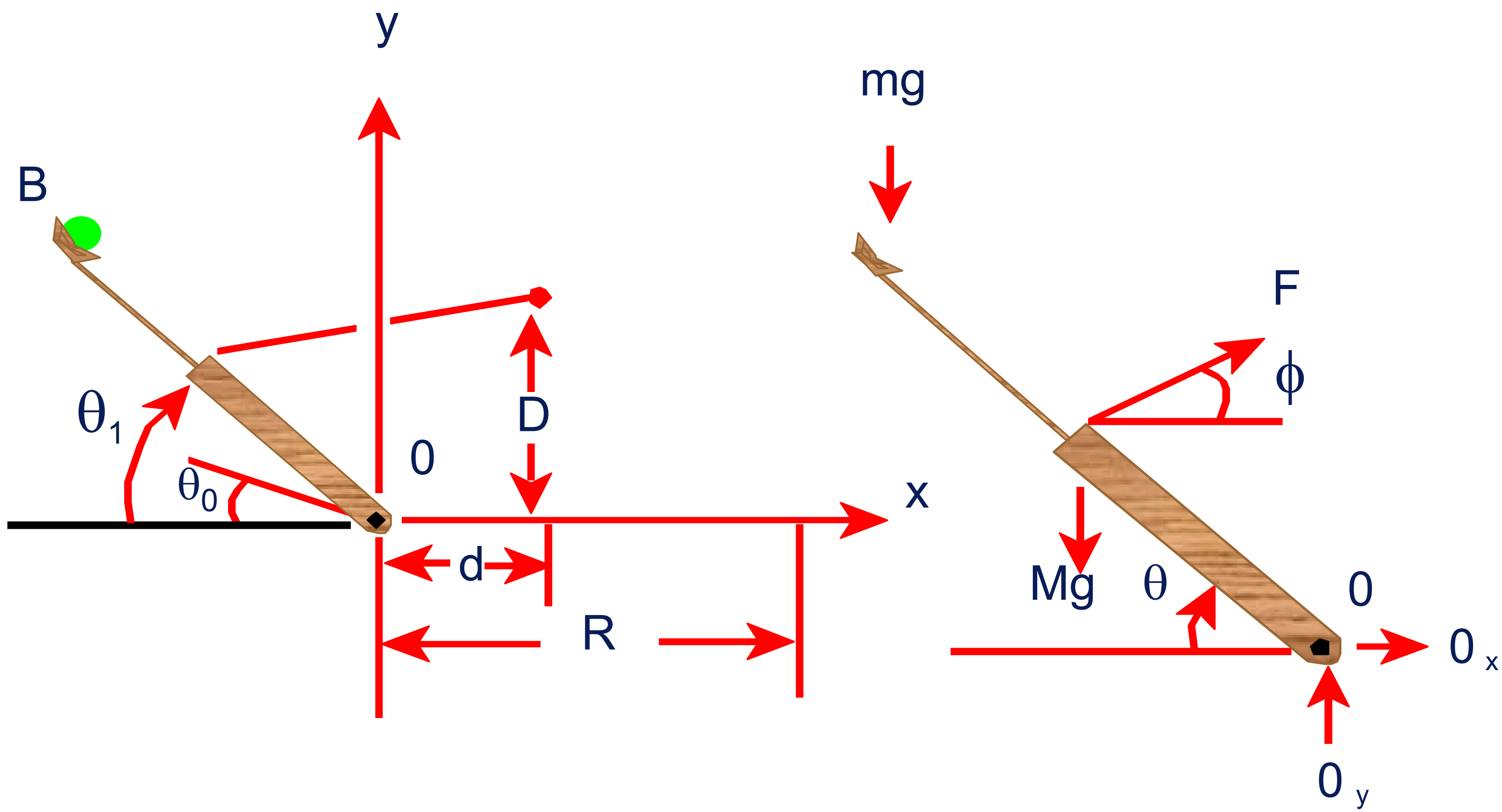
Respondent Profiles

* 18 different product profiles

Catapulting Power into Modeling

Statapult® Catapult

Catapulting Power into Modeling



The Theoretical Approach

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

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

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

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

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

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

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

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Statapult® Exercise
(DOE demonstration)

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

	A	B	AB
Avg –			
Avg +			
Δ			

$\hat{Y} =$

KISS Guidelines for Choosing an Experimental Design

KISS - Keep It Simple Statistically

Source: Steve Schmidt
Mark Kiemele
Cass Grandone

PF → **Process flow diagram**

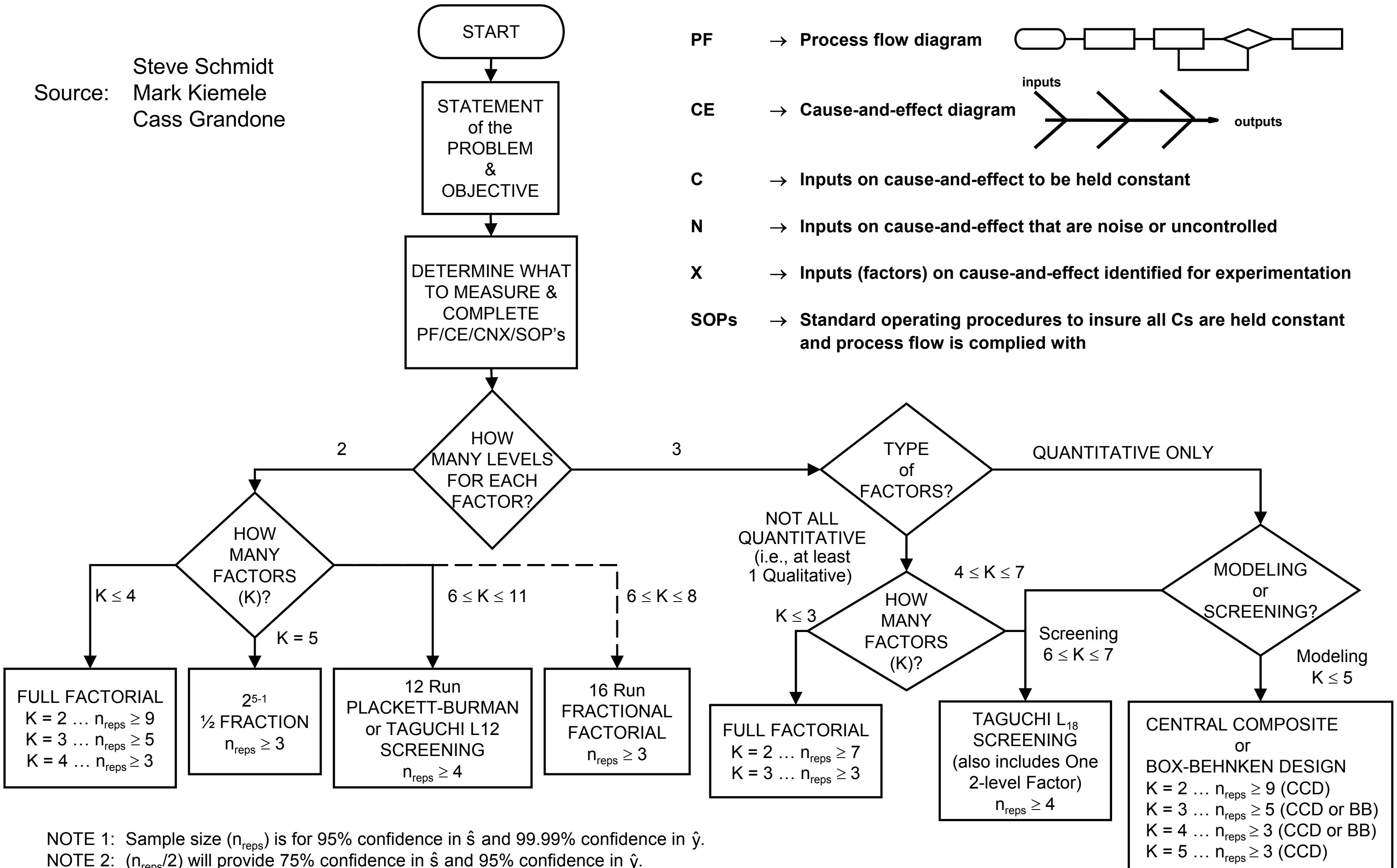
CE → **Cause-and-effect diagram**

C → **Inputs on cause-and-effect to be held constant**

N → **Inputs on cause-and-effect that are noise or uncontrolled**

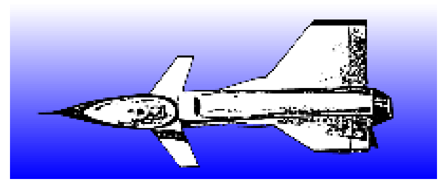
X → **Inputs (factors) on cause-and-effect identified for experimentation**

SOPs → **Standard operating procedures to insure all Cs are held constant and process flow is complied with**



NOTE 1: Sample size (n_{reps}) is for 95% confidence in $\hat{s}$ and 99.99% confidence in $\hat{y}$.
NOTE 2: ($n_{reps}/2$) will provide 75% confidence in $\hat{s}$ and 95% confidence in $\hat{y}$.
NOTE 3: The 12 Run Plackett-Burman or L12 is very sensitive to large numbers of interactions. If this is the case, you would be better off using the 16 Run Fractional Factorial or a smaller number of variables in 2 or more full factorial experiments.
NOTE 4: For more complete 2-level design options, see next page.

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**

* Patented by Dr. Bert Silich

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

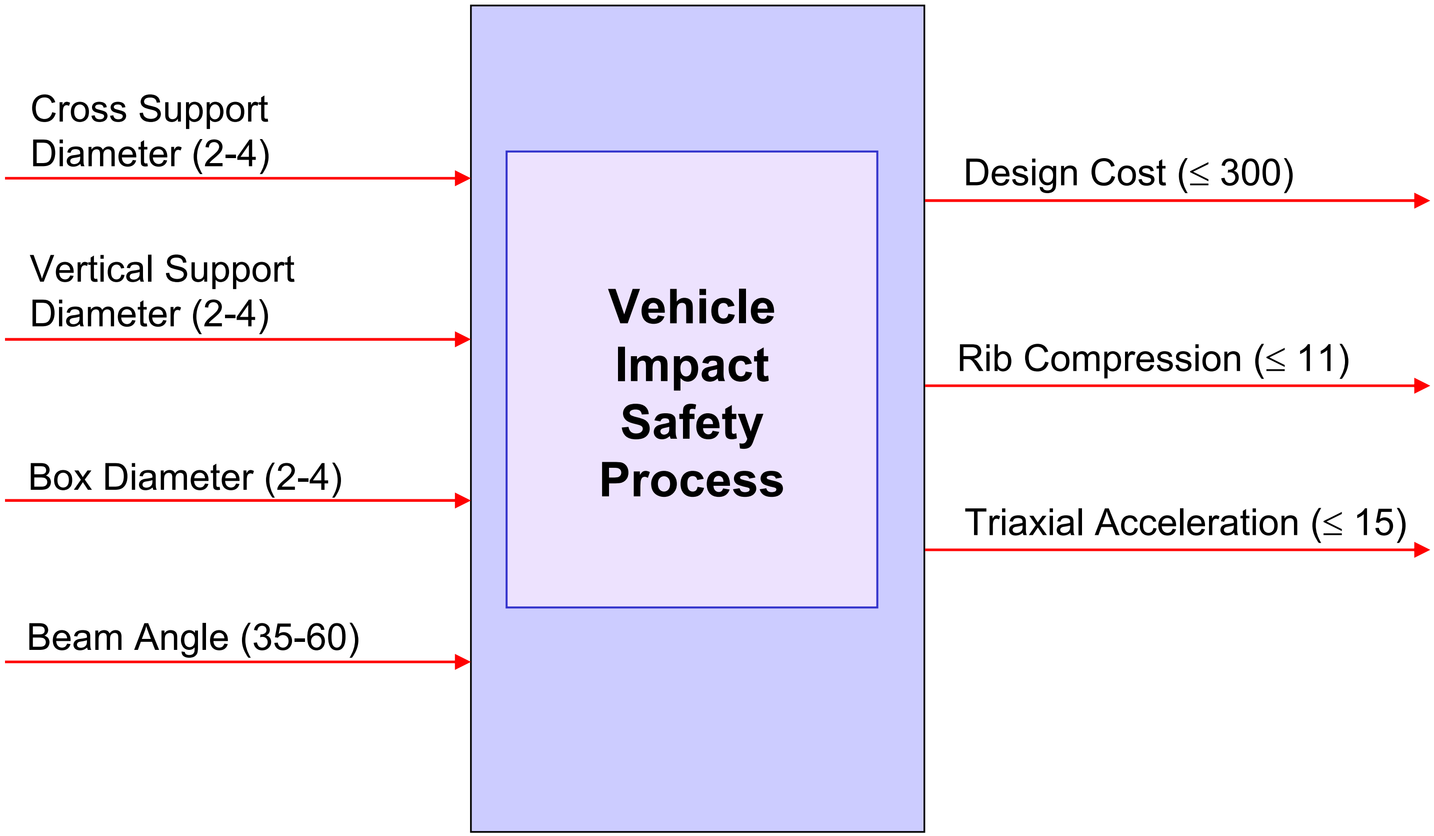
C_Y = -.006(P) - .006(R) + .169(WD1) - .121(WD2) - .063(WD3) - .004(P)(R) + .008(P)(WD1) - .006(P)(WD2) - .008(P)(WD3) - .012(R)(WD1) - .029(R)(WD2) + .048(R)(WD3) - .008(WD1)^2

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)

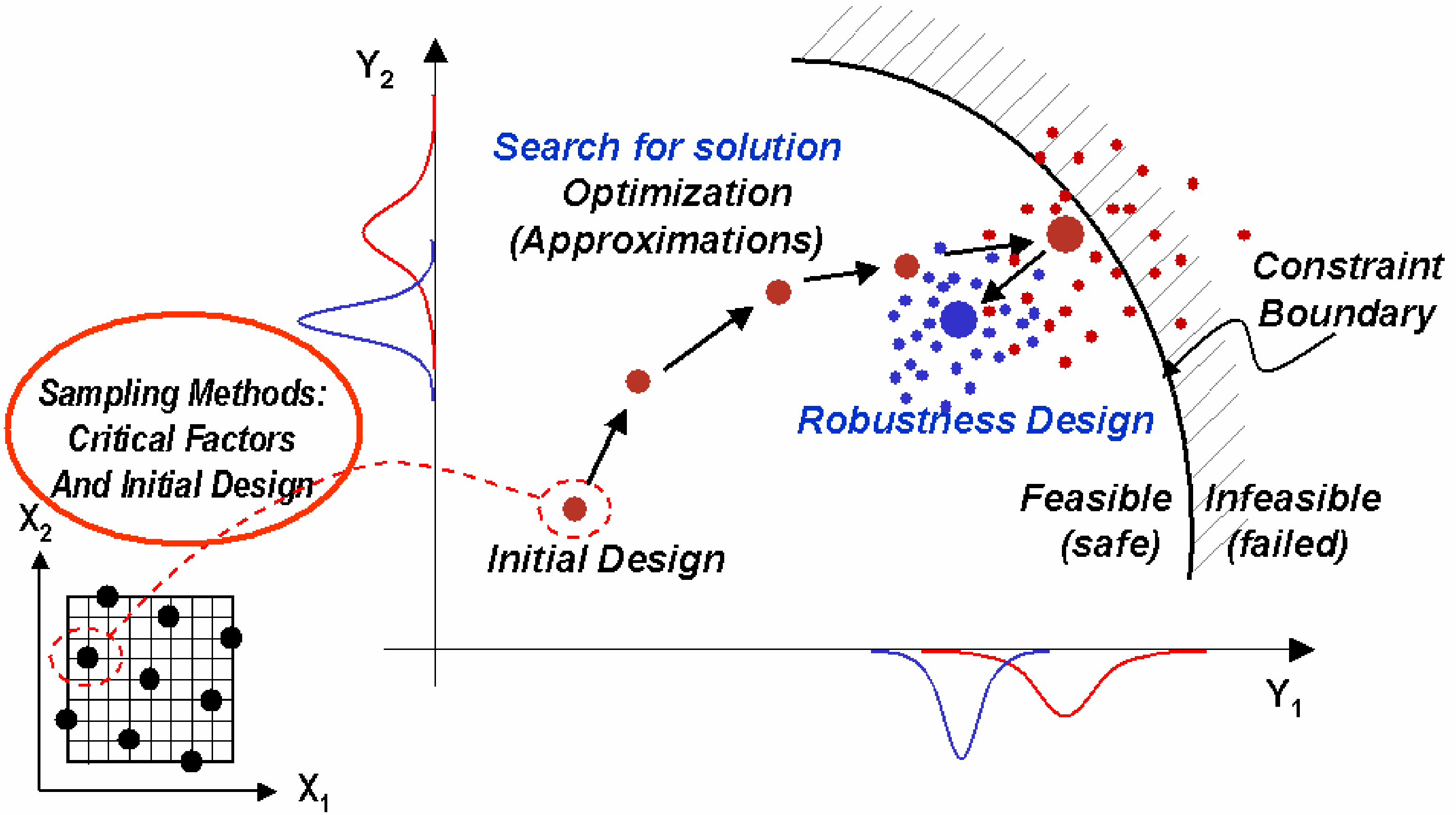
C_{YM}= .001(P) + .001(R) - .050(WD1) + .029(WD2) + .012(WD3) + .001(P)(R) - .005(P)(WD1) - .004(P)(WD2) - .004(P)(WD3) + .003(R)(WD1) + .008(R)(WD2) - .013(R)(WD3) + .004(WD1)^2 + .003(WD2)^2 - .005(WD3)^2

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)

Multiple Response Optimization Simulation Example



Iterative Use of Simulation and Modeling



Applying Modeling and Simulation to Automotive Vehicle Design

IDENTIFY CTCs, CDPs → Many, Many x's → **SCREENING DESIGN (DOE PRO)** → The critical few CDP's

SCREENING DESIGN (DOE PRO) ↔ NASTRAN RADIOSS MADYMO

Integrated processes with high fidelity CAE analyses on HPC servers

IDENTIFY CTCs, CDPs ↔ Examples of CTCs:

y_1 = weight of vehicle

y_2 = cost of vehicle

Safety CTCs with constraints specified by FMVSS (Federal Motor Vehicle Safety Standards):

- y_3 = frontal head impact
- y_4 = frontal chest impact
- y_5 = toe board intrusion
- y_6 = hip deflection
- y_7 = rollover impact
- y_8 = side impact

(y_3–y_8: RADIOSS, DYNA, MADYMO)

no federal requirements on these CTCs:

- y_9 = internal aerodynamics (airflow)
- y_{10} = external aerodynamics (airflow)
- y_{11} = noise
- y_{12} = vibration (e.g., steering wheel)
- y_{13} = harshness (e.g., over bumps, shocks)
- y_{14} = durability (at 100K miles)

(y_9–y_{10}: CFD; y_{11}–y_{14}: NASTRAN)

IDENTIFY CTCs, CDPs ↔ Examples of Critical Design Parameters (CDPs or Xs):

x_1 = roof panel material

x_2 = roof panel thickness

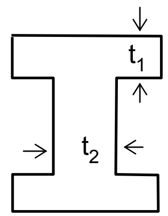
x_3 = door pillar dimensions ⇒ i beam

x_4 = shape/geometry

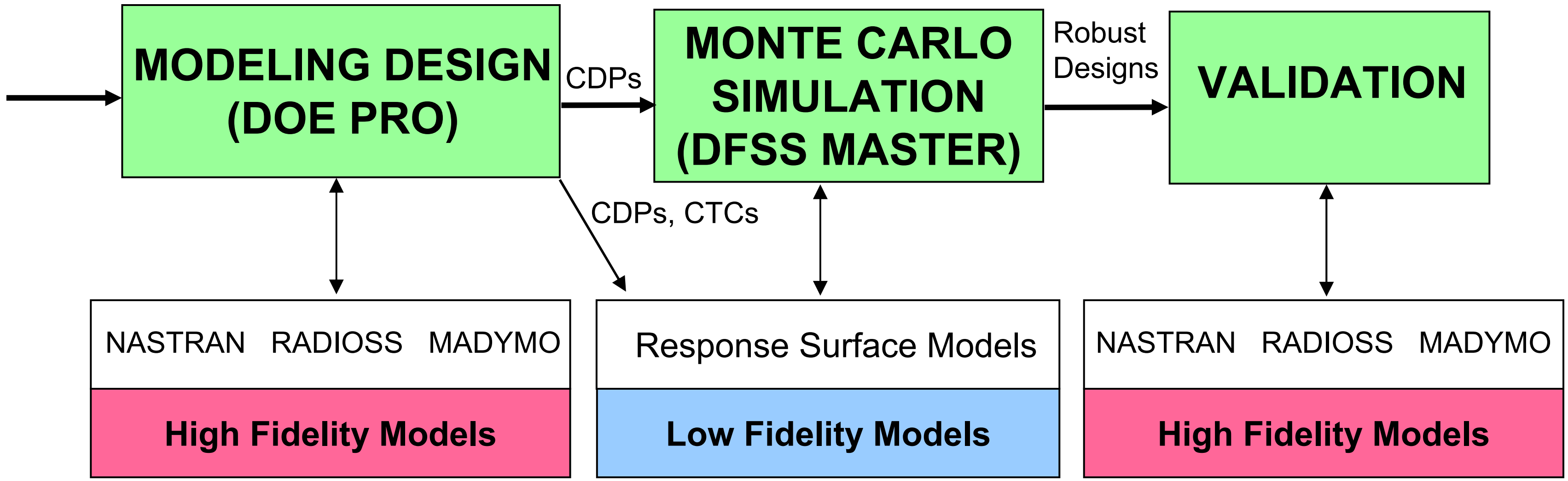
x_5 = windshield glass

x_6 = hood material, sizing and thickness

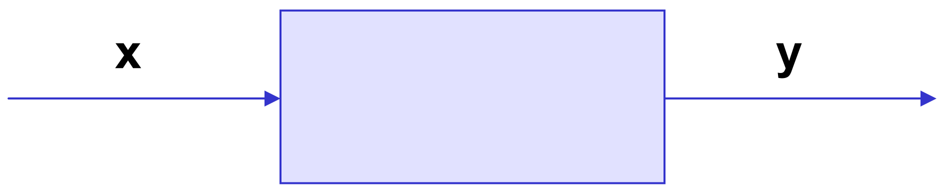
x_7 = under hood panel material, sizing and thickness



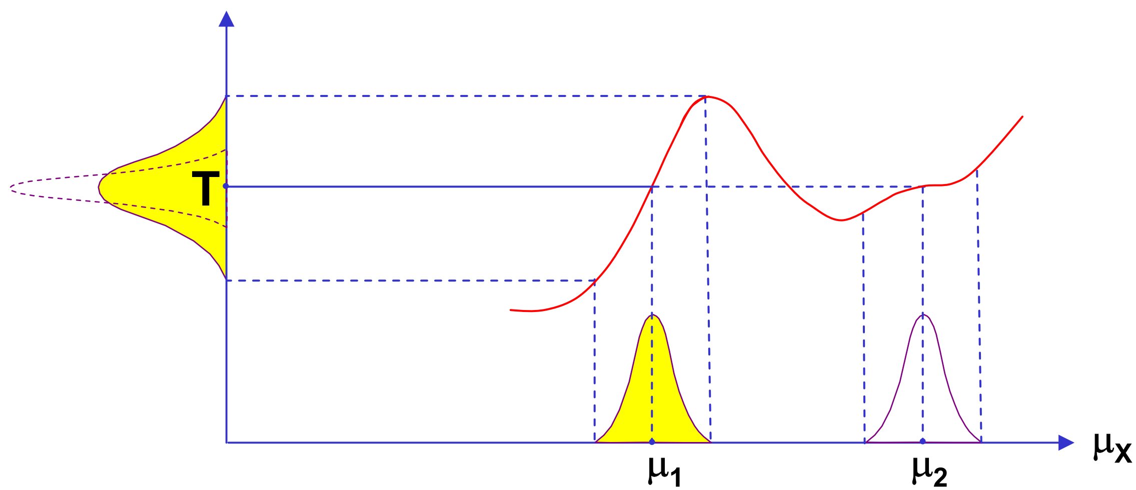
Applying Modeling and Simulation to Automotive Vehicle Design (cont.)



Why Robust Design?

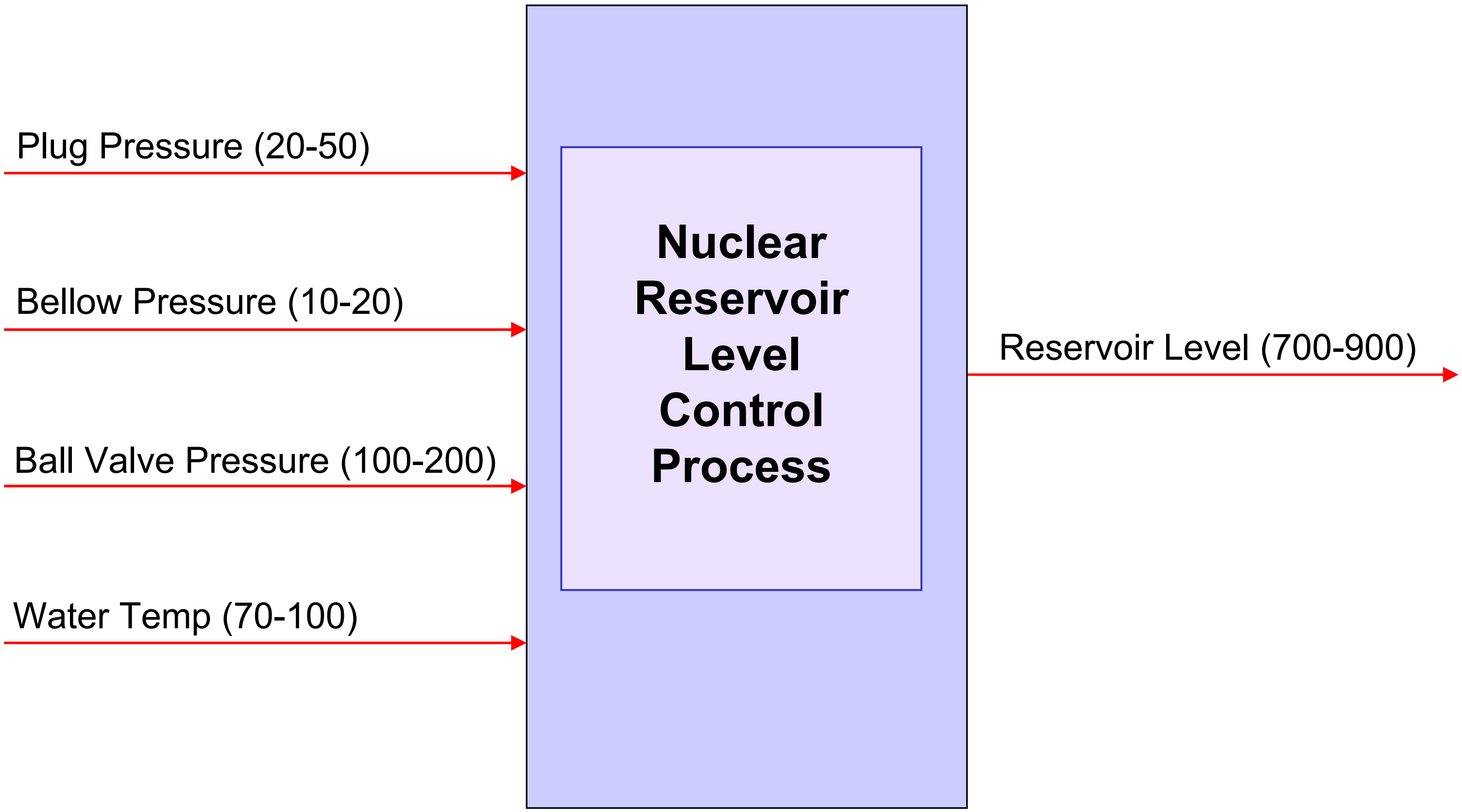


One Input

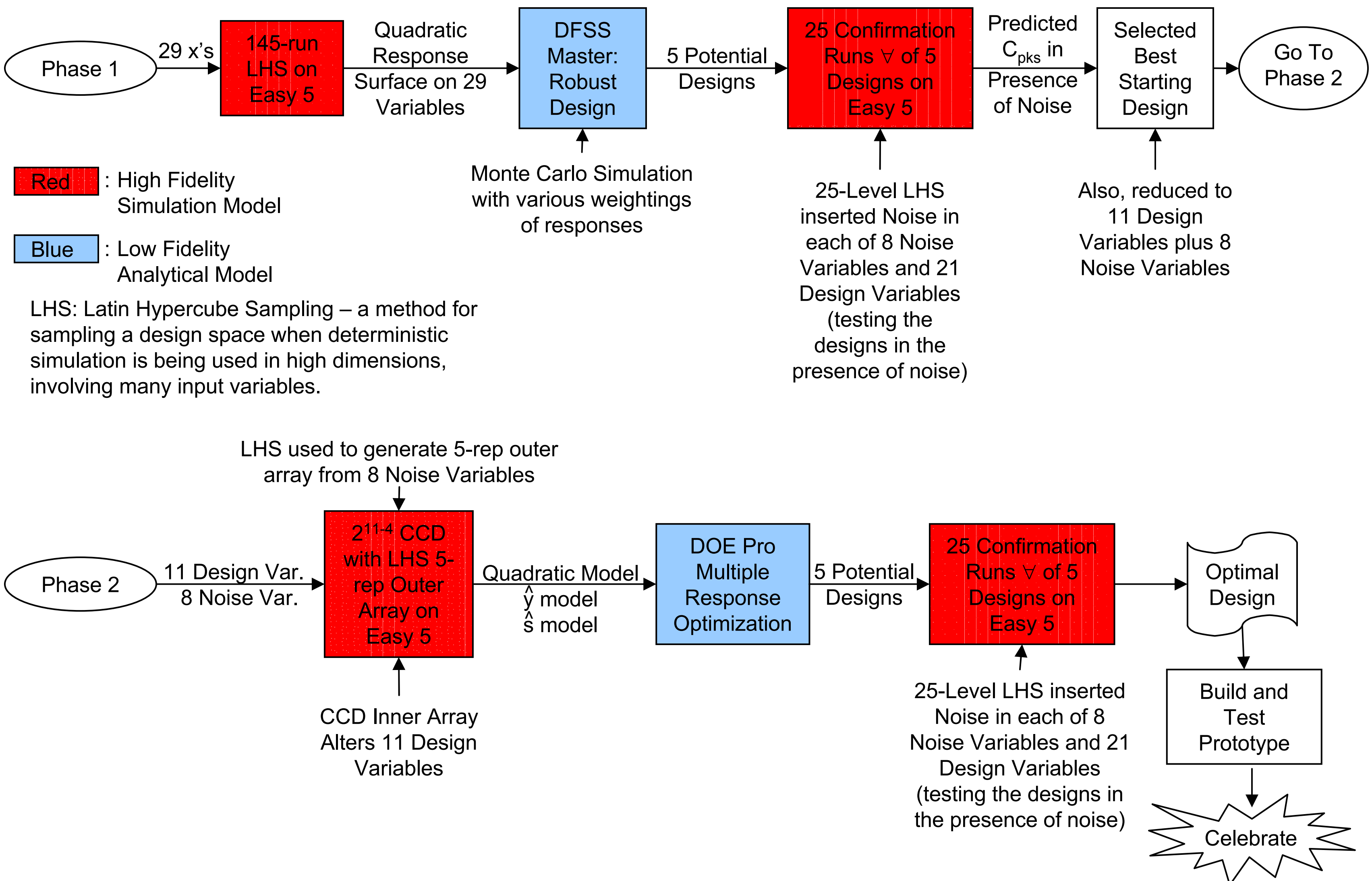


If μ_X varies, should we select μ_1 or μ_2 to hit y = T?

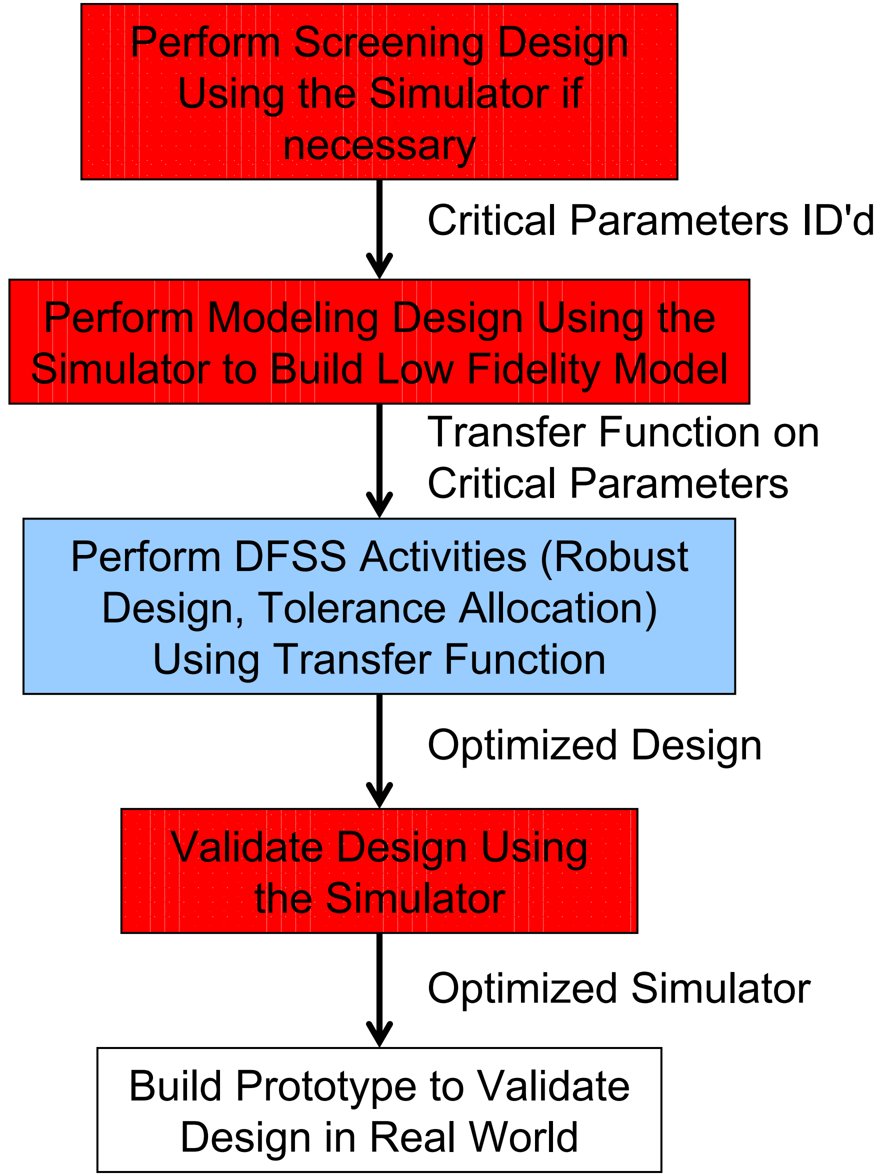
Robust (Parameter) Design Simulation Example



Example of Iterative Approach to Modeling and Simulation to Optimize Transmission Performance



Modeling the Simulator



Environments Where Simulation and Modeling Is Beneficial

- A high number of design variables
- A substantial number of design subsystems and engineering disciplines
- Interdependency and interaction between the subsystems and variables
- Multiple response variables
- Need to characterize the system at a higher level of abstraction
- Time and/or space must be compressed

The Vision of DFSS

Reactive Design Quality → DFSS → Predictive Design Quality

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

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