Design Optimization for Six-Sigma Quality

by
Dr. Andreas Vlahinos
Principal, Advanced Engineering Solutions LLC

Dr. Terry Penney, Program Manager,
NREL, Center for Transportation Technologies and Systems

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Agenda

- Introduction to DFSS, Robust Design, PIDO
- Example 1: HEV Battery
- Example 2: BIW Door assembly
- Example 3: Turbine - Integration into Product Development
- Workflow
- Recommendations

Contradicting Design Requirements

The need for innovative tools is apparent now more than ever as more complex design requirements are surfacing such as:

- Cost
- Performance & safety
- Quality
- Time to market & short life cycle
- Environmental impacts
- Aesthetics

Statistical Design Performance Simulation?

" You 've got to be passionate lunatics about the quality issue …"
Jack Welch

"U.S. autos fight poor quality reputation …"
Joe Miller / The Detroit News

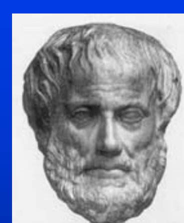
" Product quality requires managerial, technological and statistical concepts throughout all the major functions of the organization …"
Josheph M. Juran

Variation (thickness, properties, surface finish, loads, processes etc.) is … *THE ENEMY*

DOE, Design for Six Sigma (DFSS), Statistical FEA, Behavioral Modeling is … *THE DEFENCE*

Design Optimization –DFSS - PIDO

" For the goal is not the last, but the best "
Aristotle (384-322 BCE)



Design Optimization is the selection of the best alternative within the available means

Design Optimization can be addressed with:
- Knowledge, Tradition and Experience
- Numerical Optimization Methods
- Design Space exploration Methods

DFSS is set of tools and methods for Analyzing, Allocating, and Optimizing Variability

PIDO Process Integration & Design Optimization
Processes Automation ->
Design Exploration ->
Design Optimization - >
Robust Design

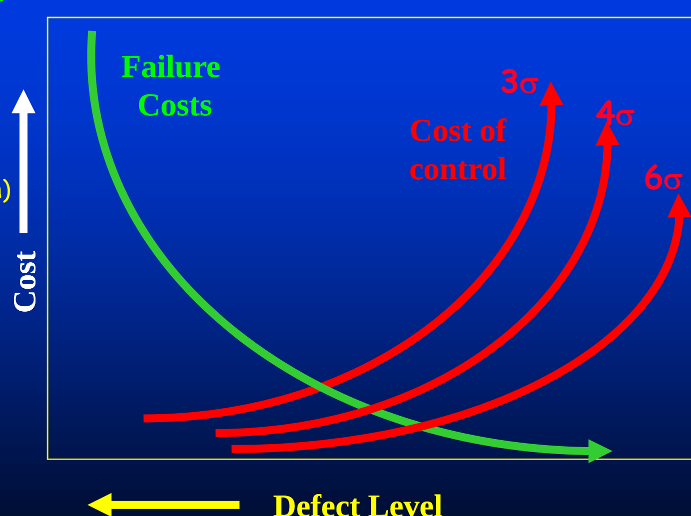
Quality - Robust Design

- **Variation** exists in all systems, subsystems, components and processes
- **Definition** of **Robust Design**: Deliver customer expectations at profitable cost regardless of:
  - customer usage
  - variation in manufacturing
  - variation in supplier
  - variation in distribution, delivery & installation
  - degradation over product life
- **Goals** of Robust Design (shrink and shift)
  - Shift performance mean to the target value
  - Shrink product's performance variability

Improved Quality and Reduced Total Cost

Cost of Defect or Failure

- Lost Customers
- Liability (R&D)
- Recalls (production)
- Rework



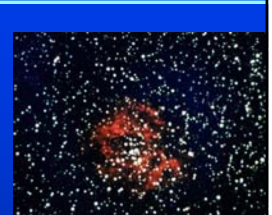
Noise & Control Parameters

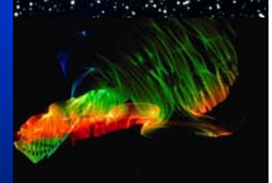
- Noise parameters:
  Factors that are beyond the control of the designer
  - material property variability
  - manufacturing process limitations
  - Environment: temperature & humidity
  - component degradation with time
  - ...

- Control Parameters:
  Factors that the designer can control
  - geometric design variables
  - material selections
  - design configurations
  - manufacturing process settings
  - ...

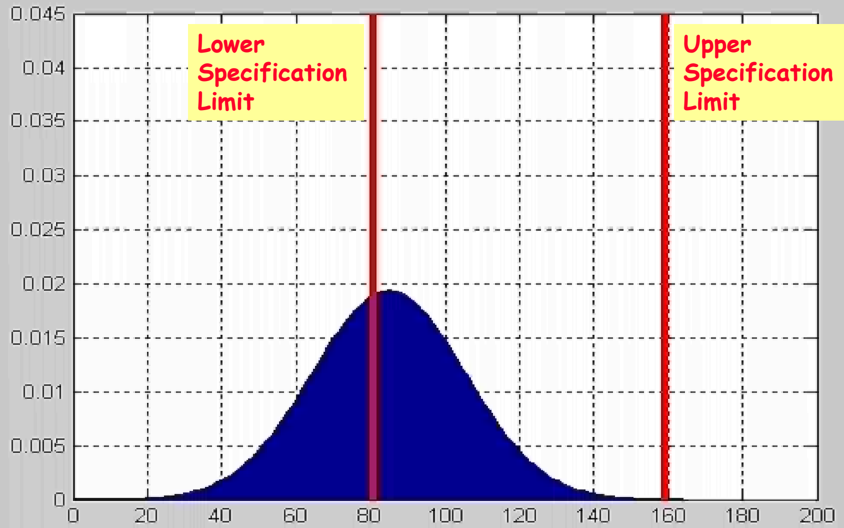
Tools for Robust Design

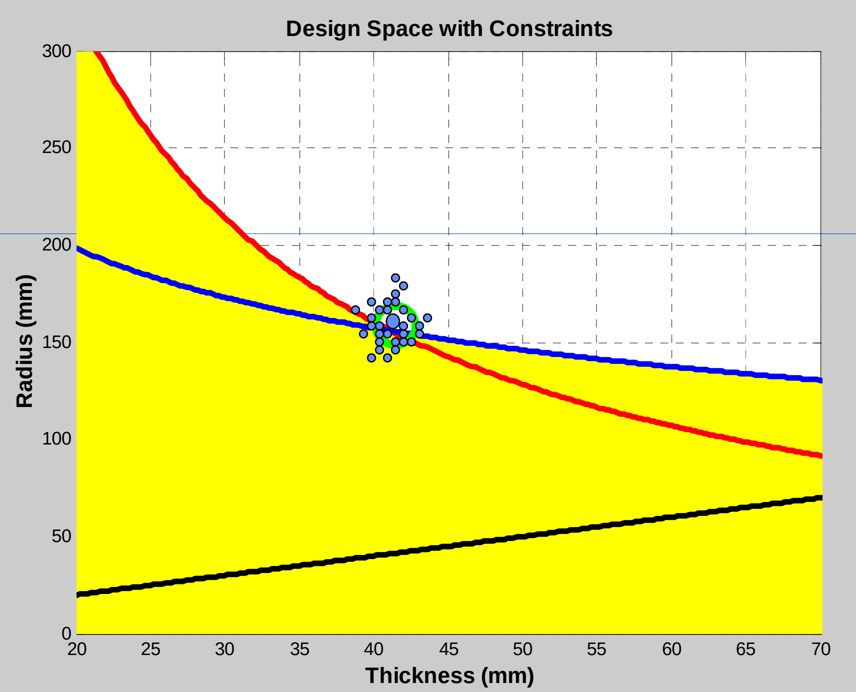
- Design Of Experiments
  - Exploits nonlinearities and interactions between noise & control parameters to reduce product performance variability
  - full factorial, fractional factorial, Monte-Carlo, LHC
- Response Surface Methods
  - Central Composite Design
  - Box-Behnken Design
- 6-sigma design
  - Identifying & qualifying causes of variation
  - Centering performance on specification target
  - Achieving Six Sigma level robustness on the key product performance characteristics with respect to the quantified variation



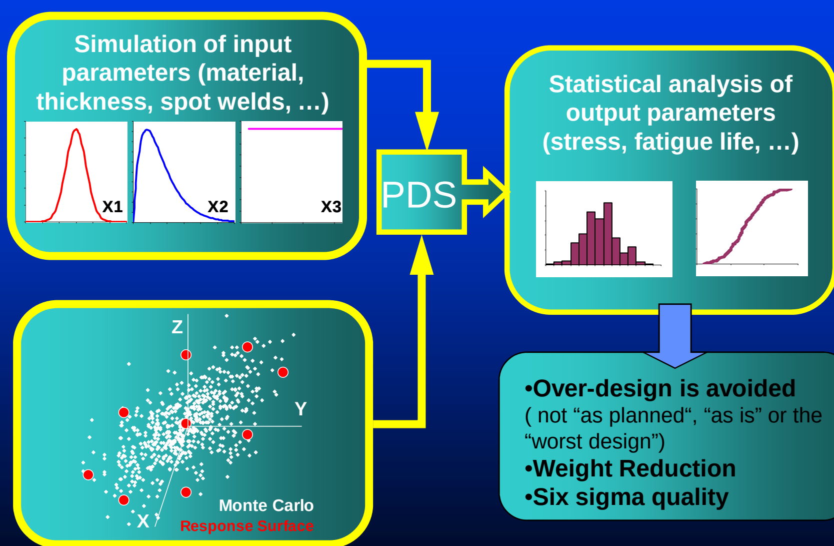


Shift and Shrink





Statistical Design Performance Simulation

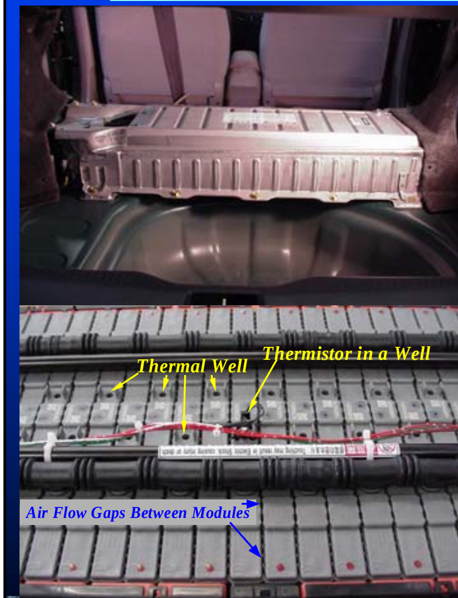


- **Over-design is avoided**
(not "as planned", "as is" or the "worst design")
- **Weight Reduction**
- **Six sigma quality**

Example # 1

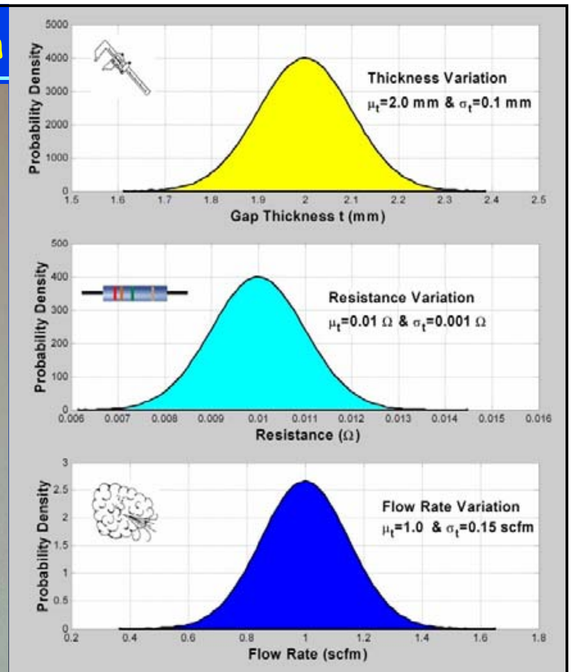
Applying Six Sigma Design Process to HEV Battery Thermal Management

HEV Battery Pack



Inputs with Variation

- Gap Thickness
- Cell Resistance
- Flow Rate
- Six input parameters:
  1. μ_{tgap}
  2. σ_{tgap}
  3. μ_R
  4. σ_R
  5. μ_{Frate}
  6. σ_{Frate}

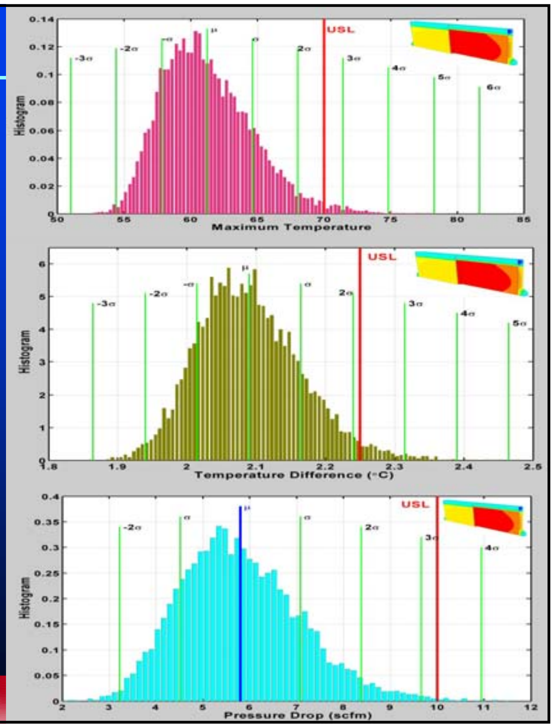


Outputs / Goals

Outputs – variation
- max temperature
- differential temperature
- pressure drop

Six output parameters:
1. μ_{Tmax}
2. μ_{dT}
3. μ_{dP}
4. σ_{Tmax}
5. σ_{dT}
6. σ_{dP}

Three Upper Specification Limits (USL)



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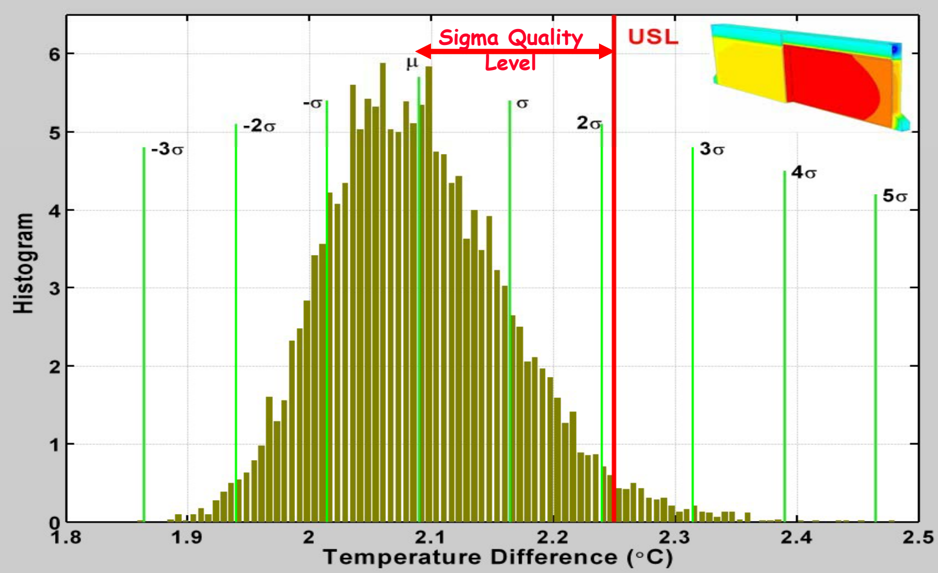
Histogram of Temperature Differential and Sigma Quality Levels



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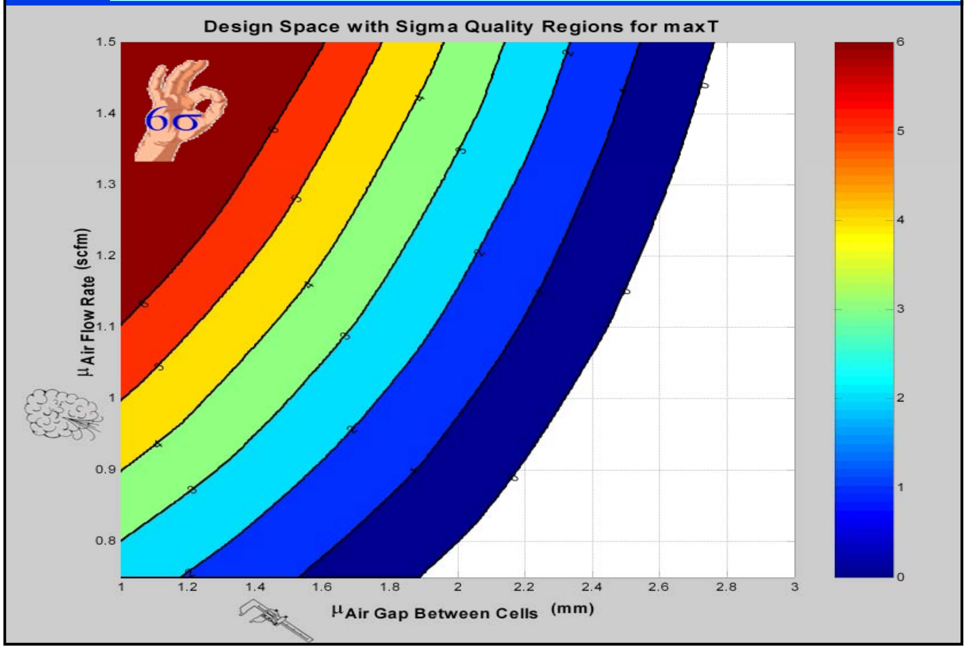
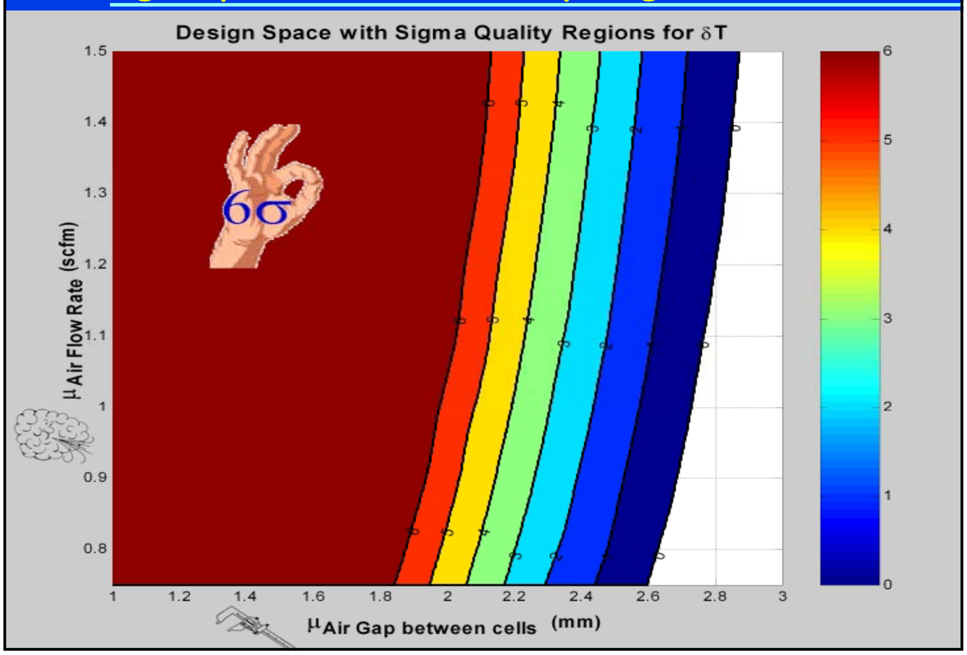
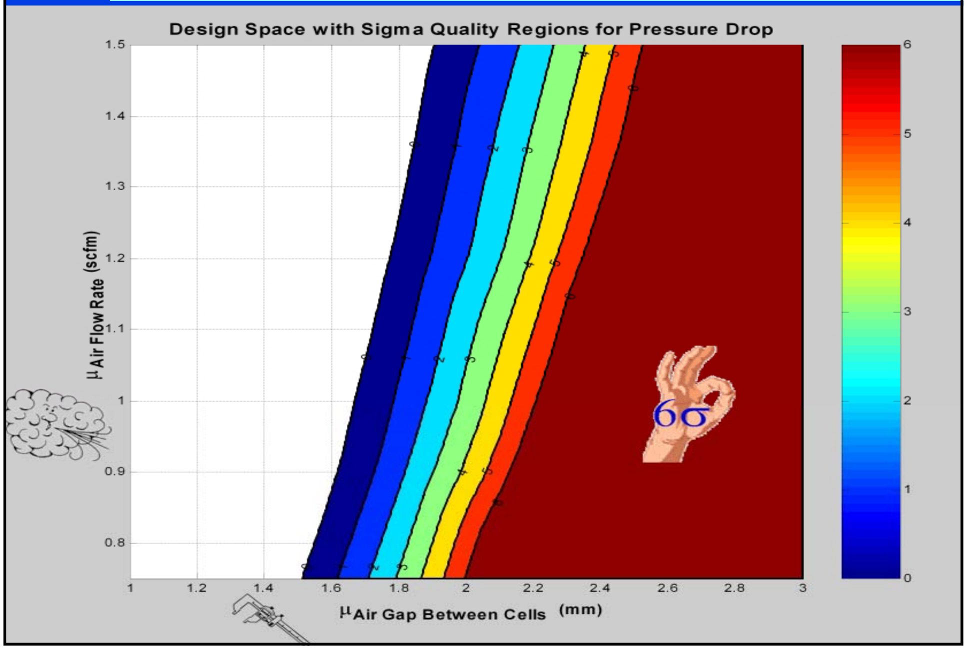
Design Space with σ Quality Regions T_{max}



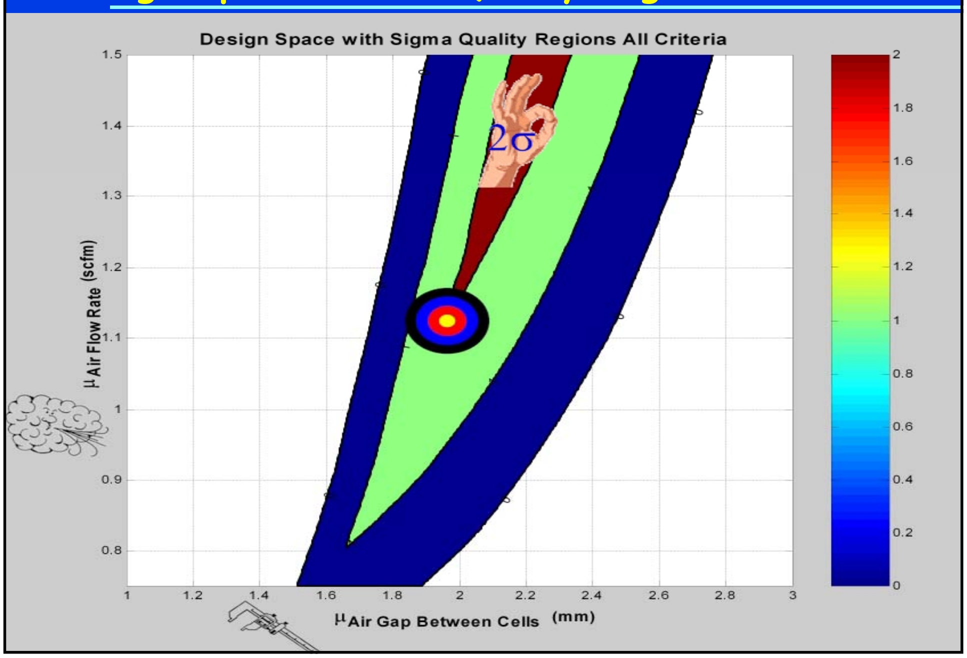
Design Space with σ Quality Regions dT



Design Space with σ Quality Regions dP



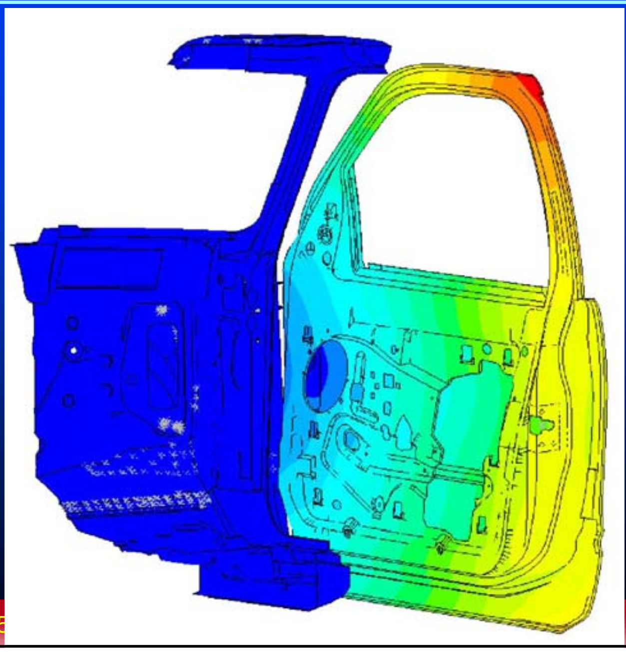
Design Space with σ Quality Regions All



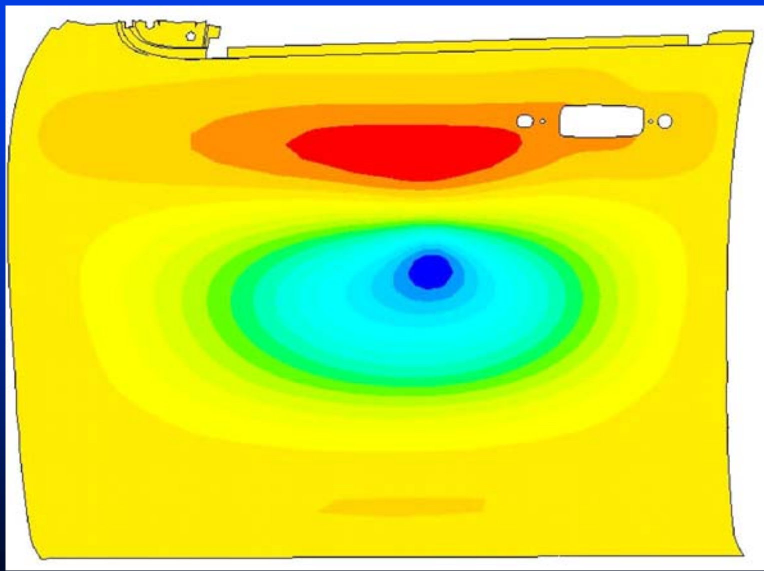
Example # 2

Effect of thickness and material variation on six-sigma performance targets of a door assembly

Door Sag Displacement Distribution



Oil-Canning Deflection Distribution



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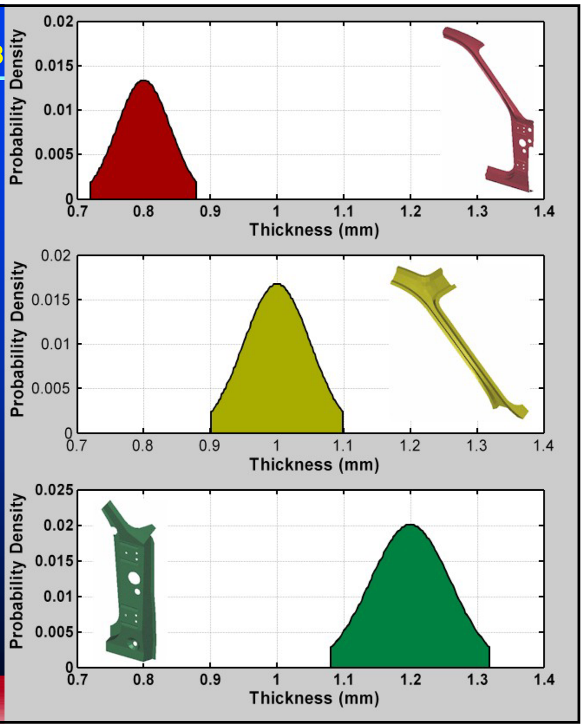
Input variables 1-3

- Thicknesses of A-pillar Components



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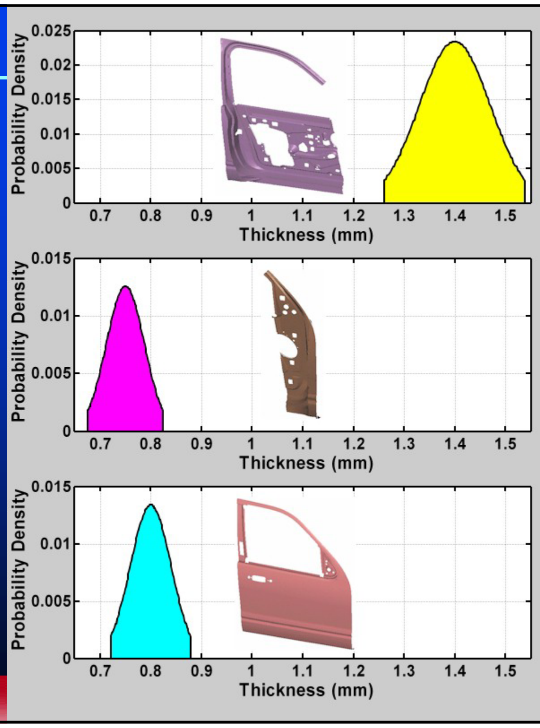
Input variables 4-6

Thicknesses of Door Components



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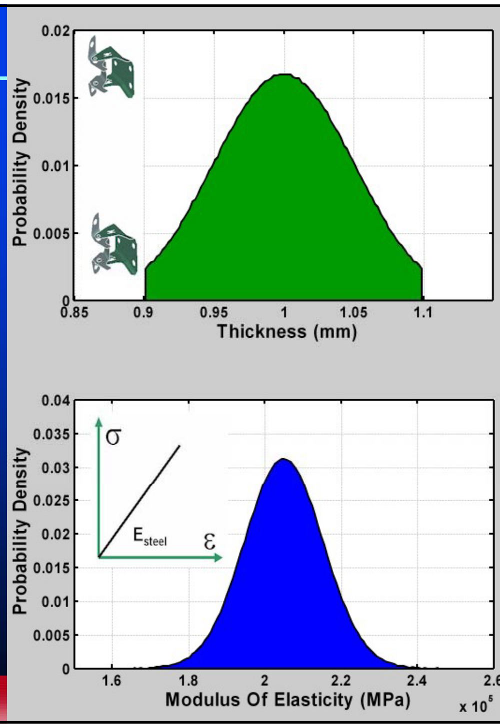
Input variables 7-8

- Thicknesses of Door Hinges
- Modules of elasticity



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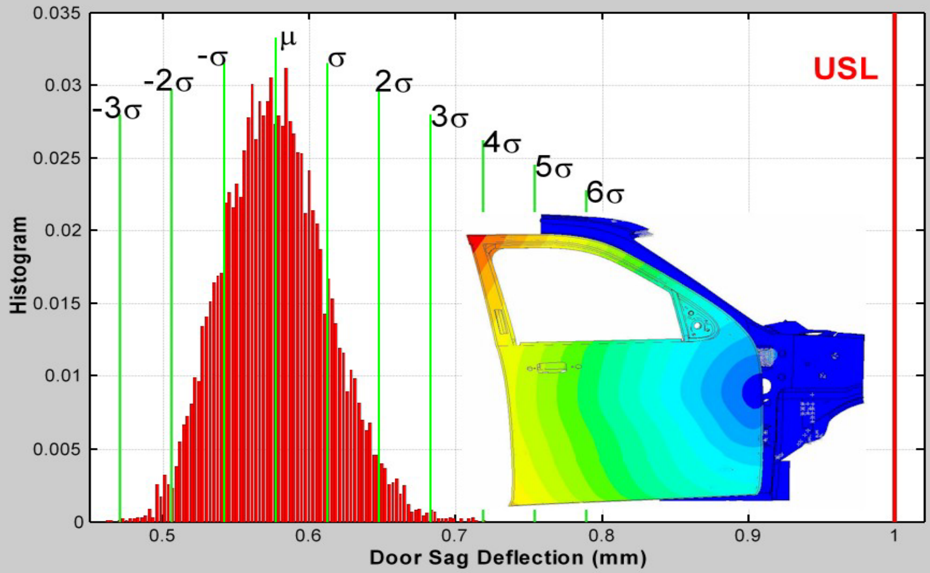
Door Sag Deflection Response Attribute # 1



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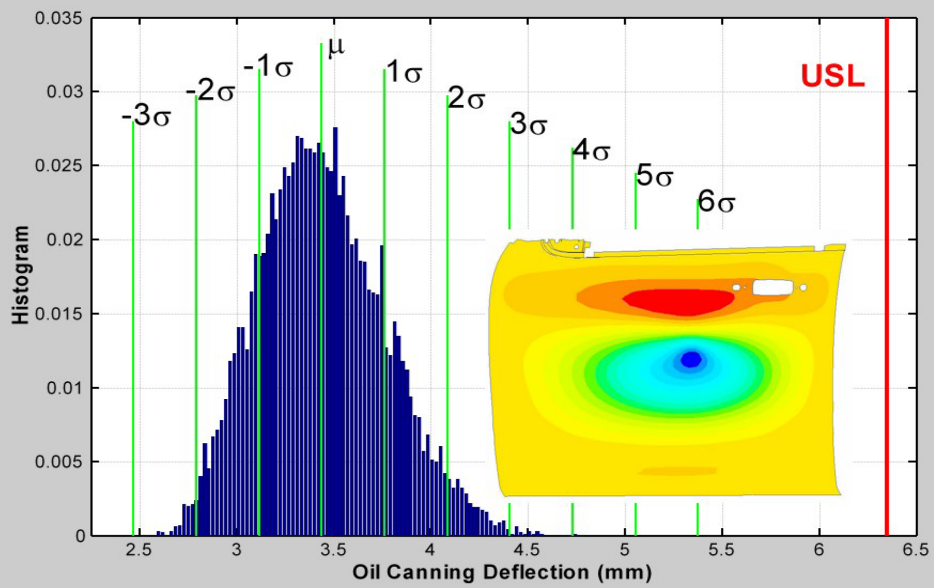
Oil-Canning Deflection Response Attribute # 2



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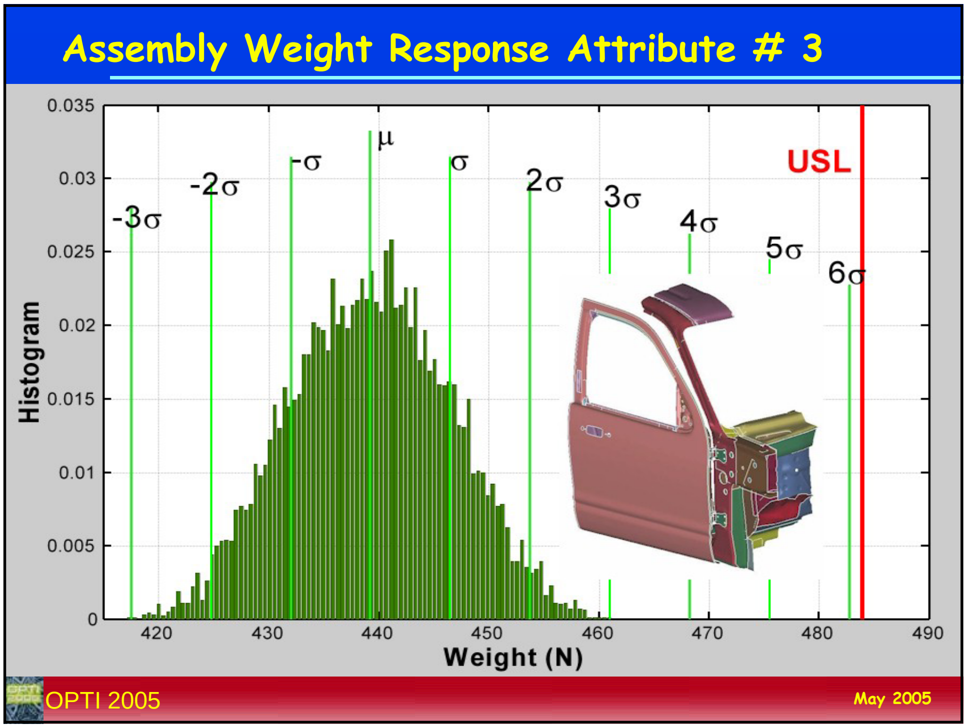
Assembly Weight Response Attribute # 3
Histogram
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
420
430
440
450
460
470
480
490
Weight (N)
-3σ
-2σ
-σ
μ
σ
2σ
3σ
4σ
5σ
6σ
USL
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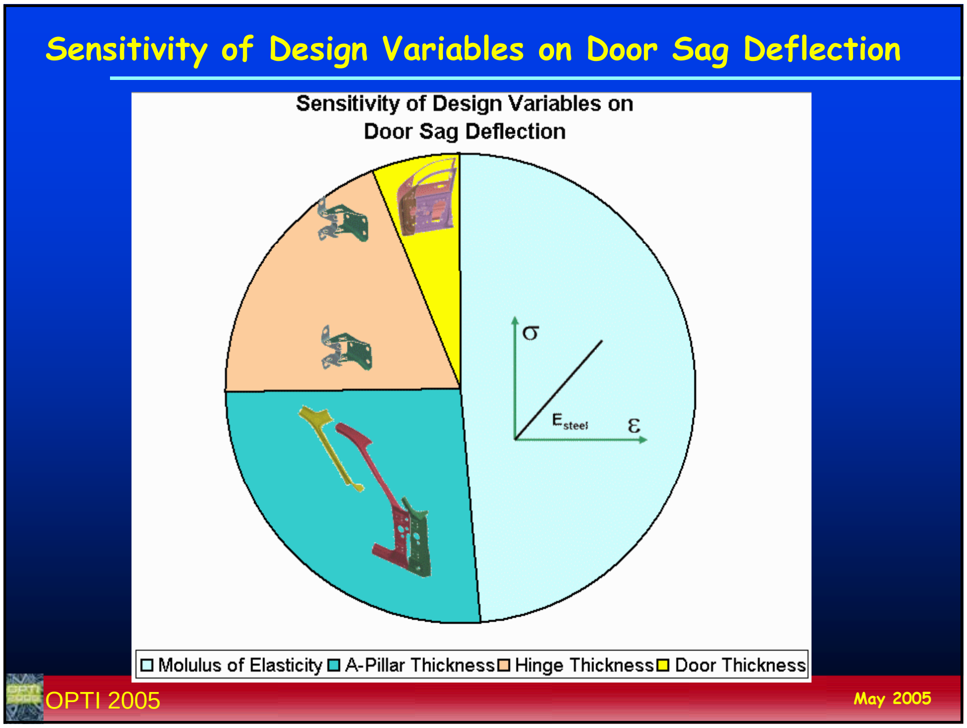
Sensitivity of Design Variables on Door Sag Deflection
Sensitivity of Design Variables on
Door Sag Deflection
σ
ε
E steel
Molulus of Elasticity
A-Pillar Thickness
Hinge Thickness
Door Thickness
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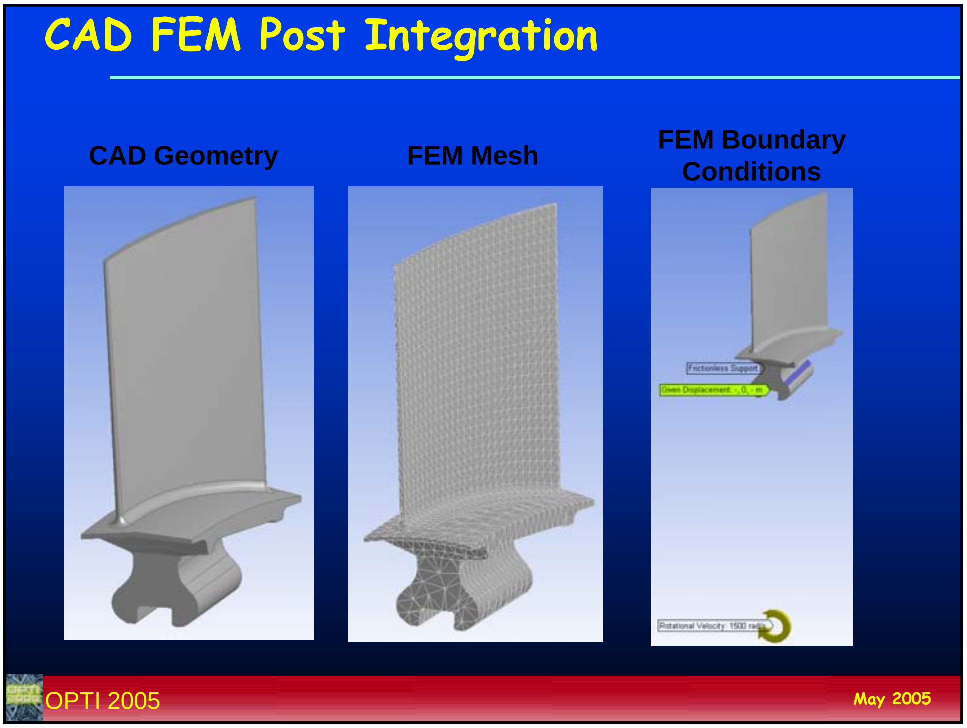

CAD FEM Post Integration
CAD Geometry
FEM Mesh
FEM Boundary Conditions
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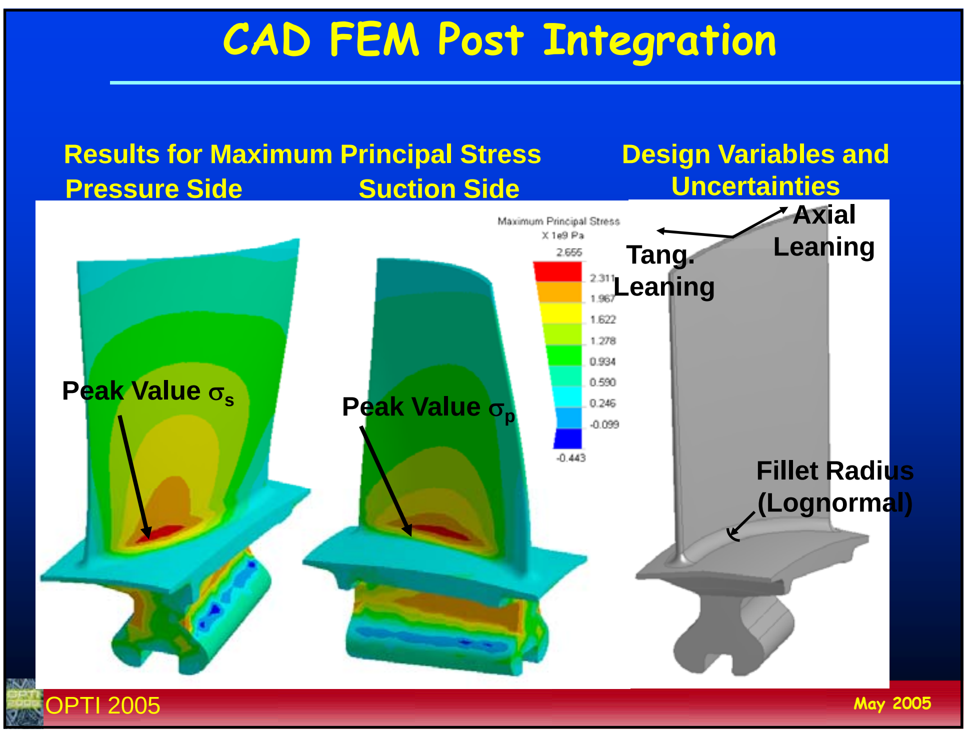

CAD FEM Post Integration
Results for Maximum Principal Stress
Pressure Side
Suction Side
Design Variables and Uncertainties
Maximum Principal Stress
X 1e9 Pa
2.655
2.311
1.967
1.622
1.278
0.934
0.590
0.246
-0.099
-0.443
Peak Value σ_s
Peak Value σ_p
Tang. Leaning
Axial Leaning
Fillet Radius (Lognormal)
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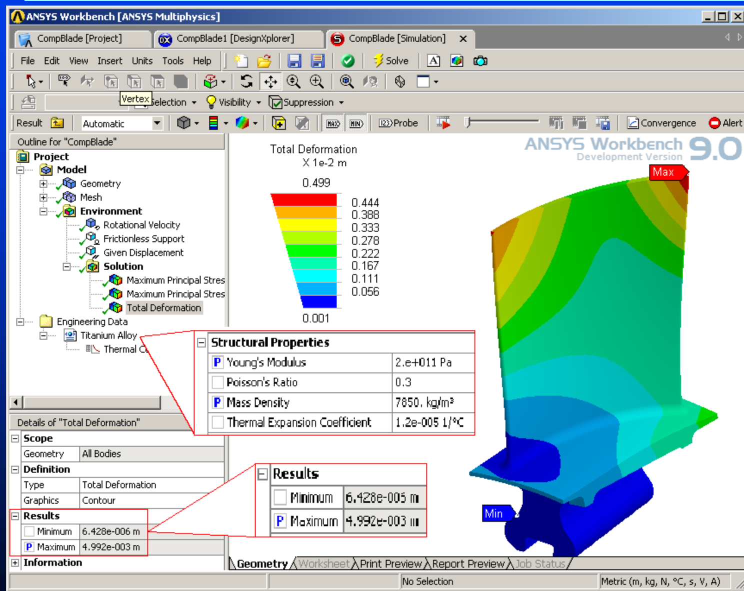
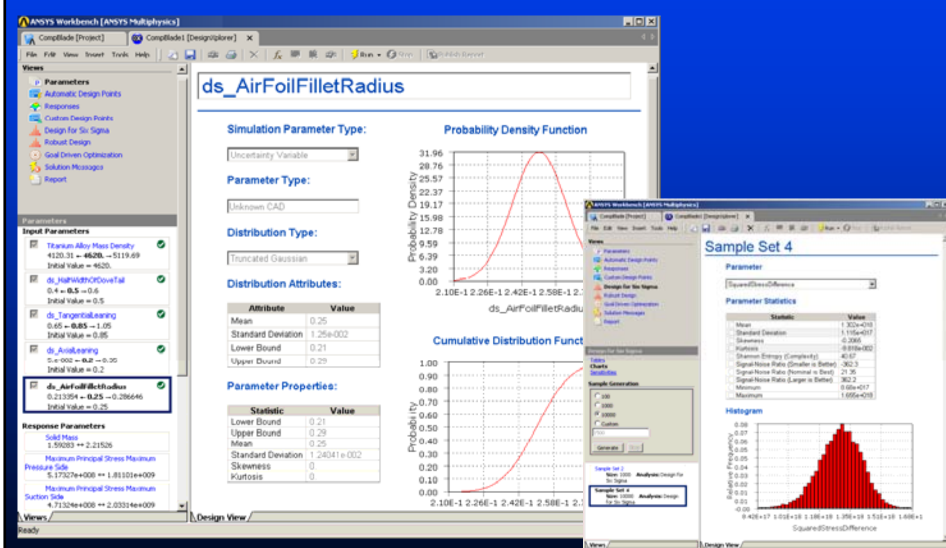
Enabling Parameterization with Workbench

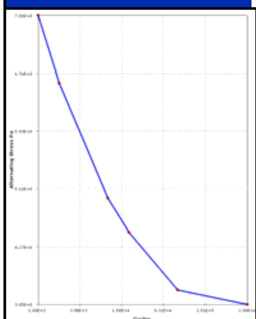


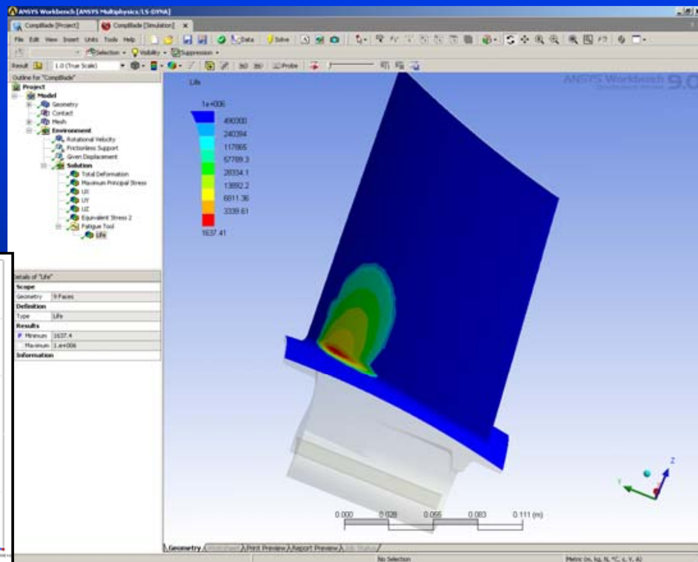
DesignXplorer manages parameters & uncertainties



Deterministic Optimization for Fatigue Life

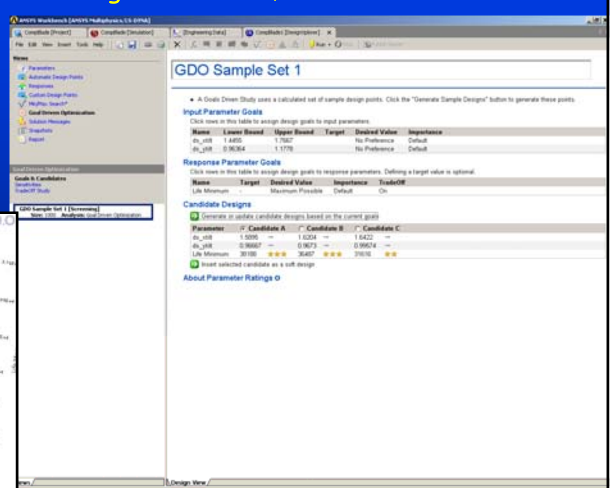
Initial Design:
Fatigue Life
1,637 Cycles

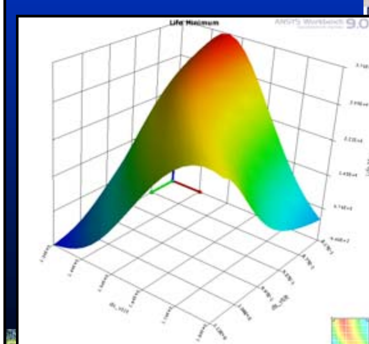


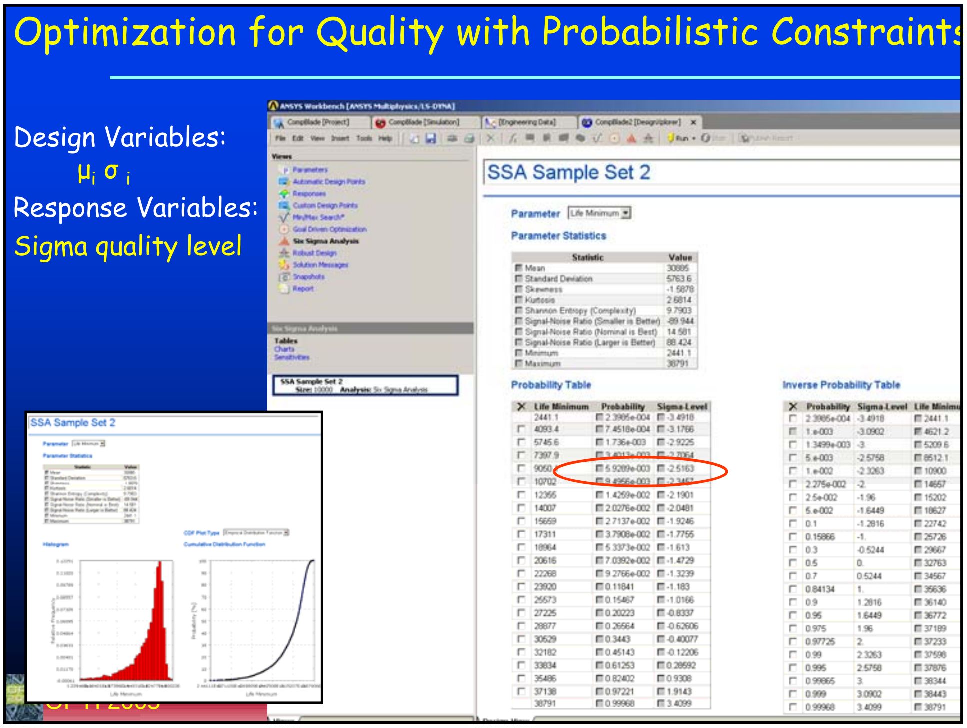


Deterministic Optimization for Fatigue Life

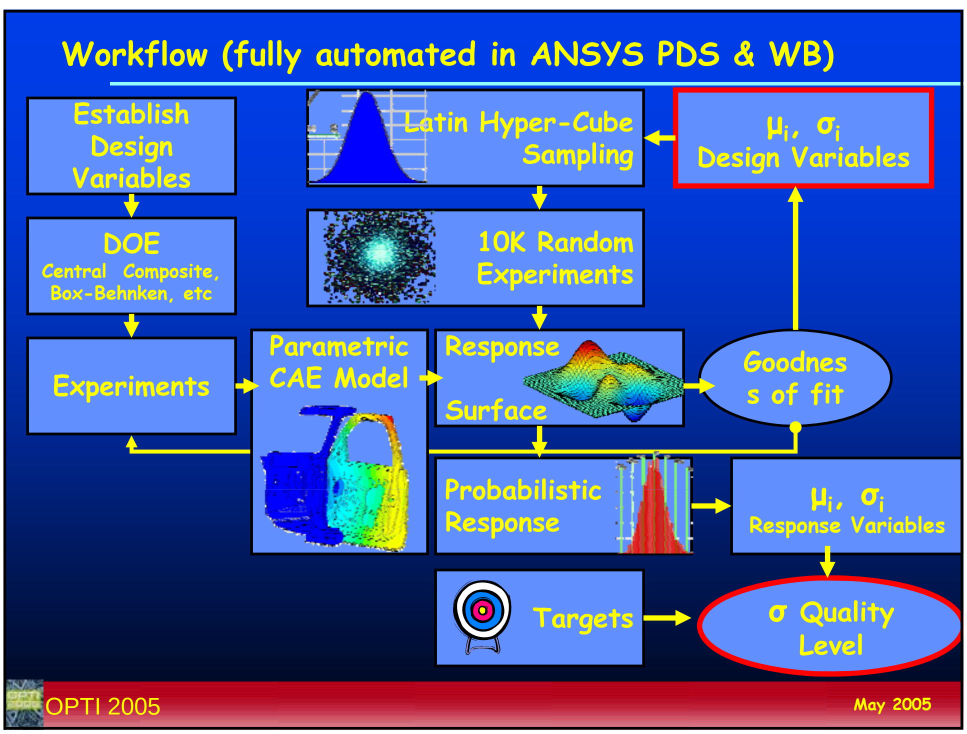
- Optimize Tilt and Lean; Fatigue Life = 38,118







Optimization for Quality with Probabilistic Constraints
Design Variables:
μi σ i
Response Variables:
Sigma quality level
SSA Sample Set 2
Parameter
Parameter Statistics
Probability Table
Inverse Probability Table



Workflow (fully automated in ANSYS PDS & WB)
Establish Design Variables
Latin Hyper-Cube Sampling
μi, σi Design Variables
DOE
Central Composite, Box-Behnken, etc
10K Random Experiments
Experiments
Parametric CAE Model
Response Surface
Goodnes s of fit
Probabilistic Response
μi, σi Response Variables
Targets
σ Quality Level
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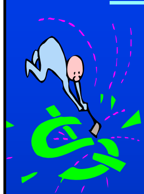
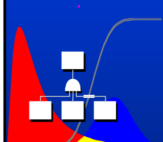
Seven Habits of Highly Effective Design Process

1. Clarify and document the desired design decision process
2. Create a design environment tailored to the desired design process with workflow management
3. Develop a repository of design & manufacturing rules to govern the design process
4. Simplify and automate tool usage for standard analyses
5. Automate and simplify data integration (get the right data the first time)
6. Augment the experts by automating large portions of the design process (Workbench wizards)
7. PIDO (DesignXplorer, Noesis, VisualDOC, iSIGHT, mode Frontier, hyperStudy, model center, RDCS, BMX, …)

Recommendations for DFSS Implementation





- Make the cost of poor quality part of the design equation

  - $Cost = C_{\text{Product Development}} + C_{\text{Warranty}} + C_{\text{Liability}} + C_{\text{Recalls}} + C_{\text{Lost Customers}} + C_{\text{Rework}} + \ldots$

- CAE analyses should include a robustness assessment for known sources of variation
- Place the power of DFSS in the hands of every designing engineer not just those with advanced engineering degrees
- Automate - Incorporate DFSS into your design process


Design-for-Six Sigma strategies are transforming
our methodologies for improving quality
from inspecting defects **to** *building quality in*