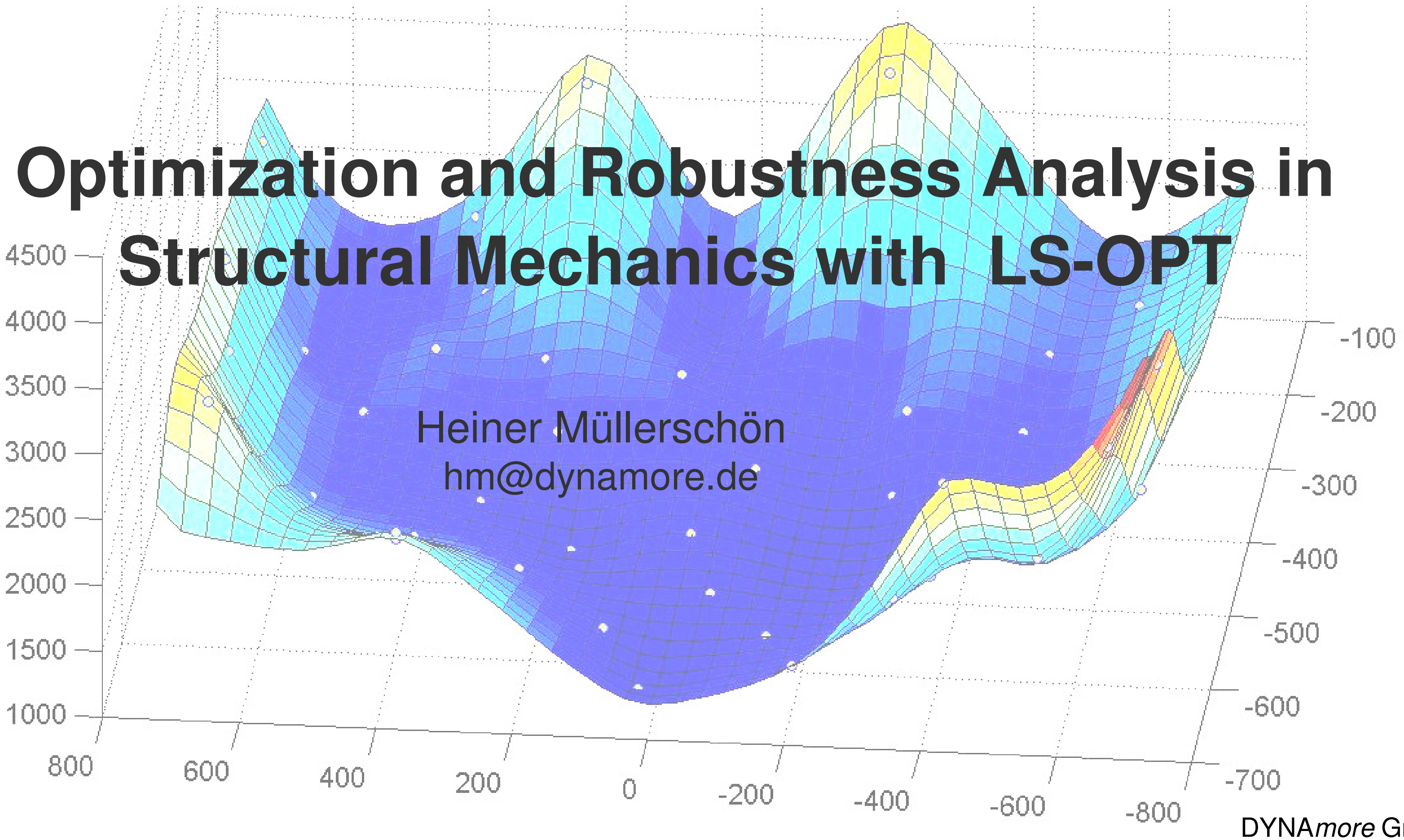
# Optimization and Robustness Analysis in Structural Mechanics with LS-OPT

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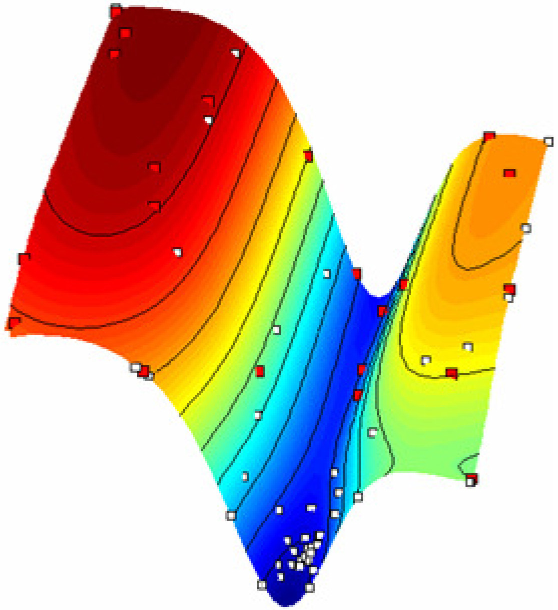
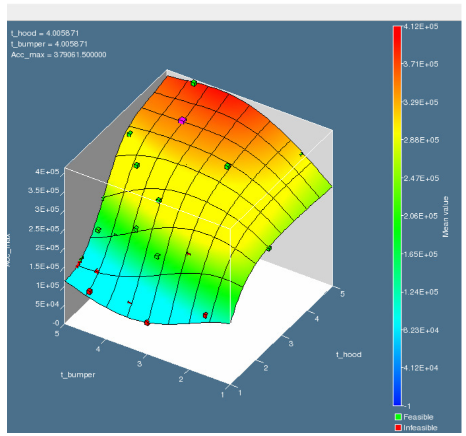
# ➔ Overview

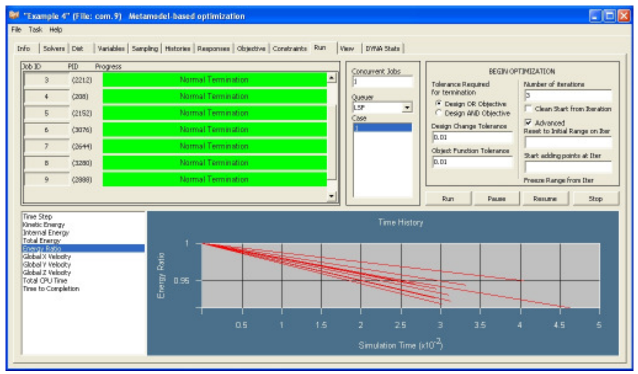
- Introduction/Features
- Methodologies – Optimization
- Methodologies - Robustness
- Examples - Optimization
- Examples - Robustness
- What's new in Version 3.2
- Outlook



## ➔ About LS-OPT

- LS-OPT is a product of LSTC (Livermore Software Technology Corporation)
- LS-OPT can be linked to any simulation code – stand alone optimization software
- Methodologies/Features:
  - *Successive Response Surface Method (SRSM)*
  - *Search Based optimization (SRS) – "moving clouds"*
  - *Reliability based design optimization (RBDO)*
  - *Multidisciplinary optimization (MDO)*
  - *Multi-Objective optimization (Pareto)*
  - *numerical/analytical based sensitivities*
  - *Analysis of Variance (ANOVA)*
  - *Stochastic/Probabilistic Analysis*
  - *Monte Carlo Analysis using Metamodels*
  - *….*

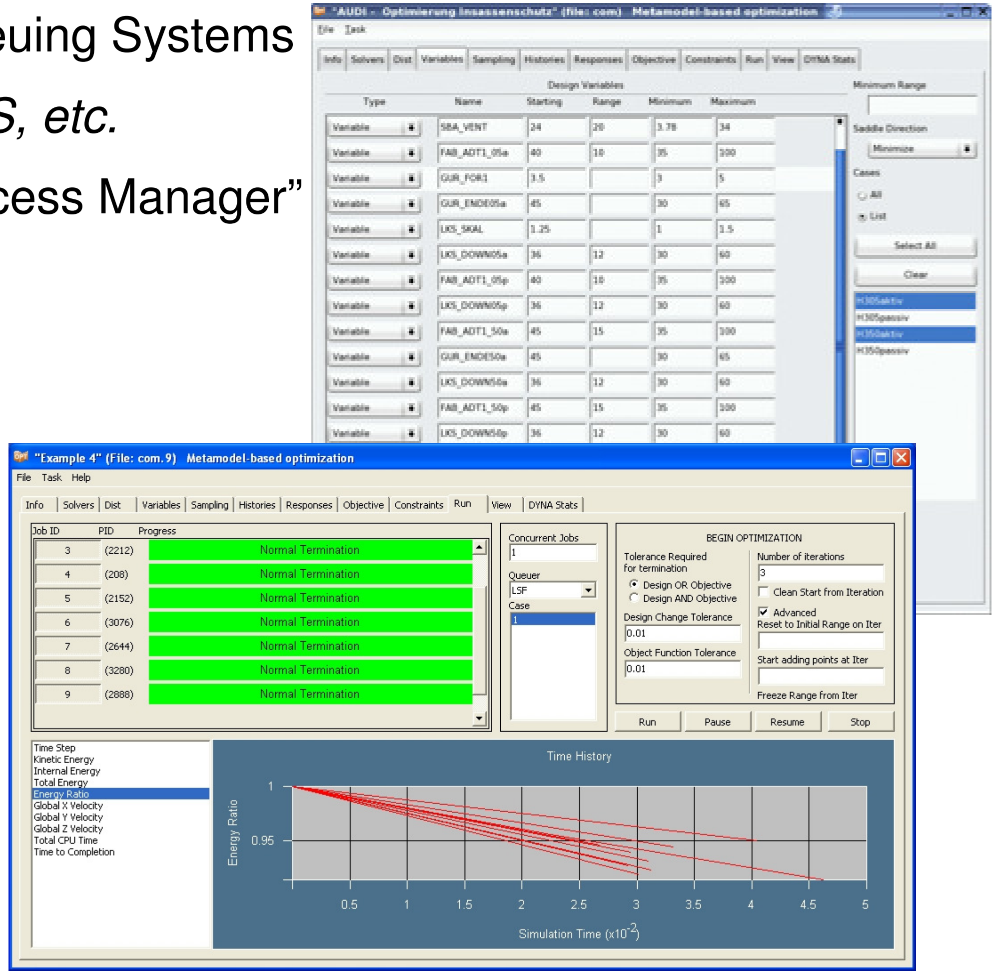




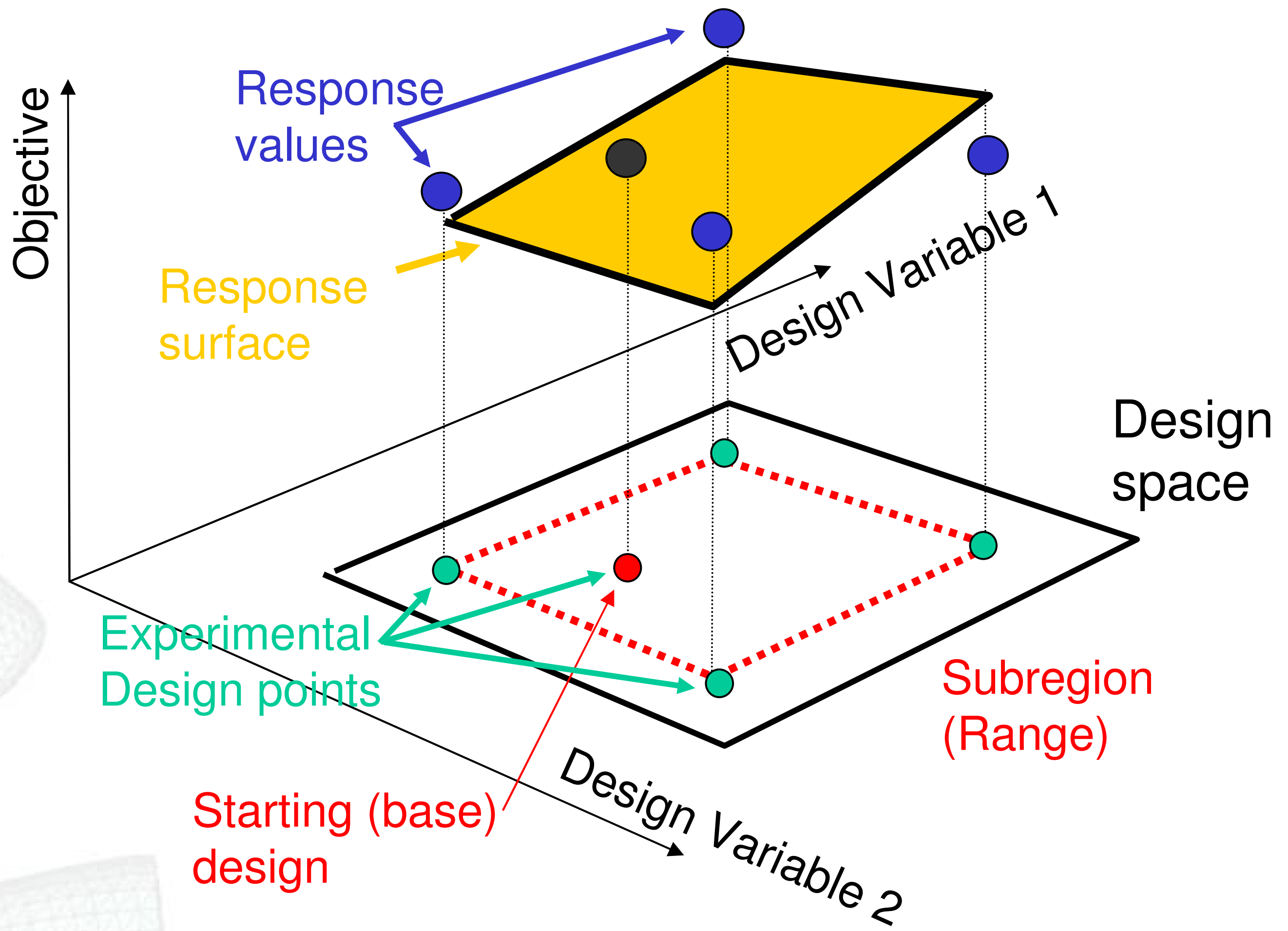
# Introduction / Features

## ➔ About LS-OPT

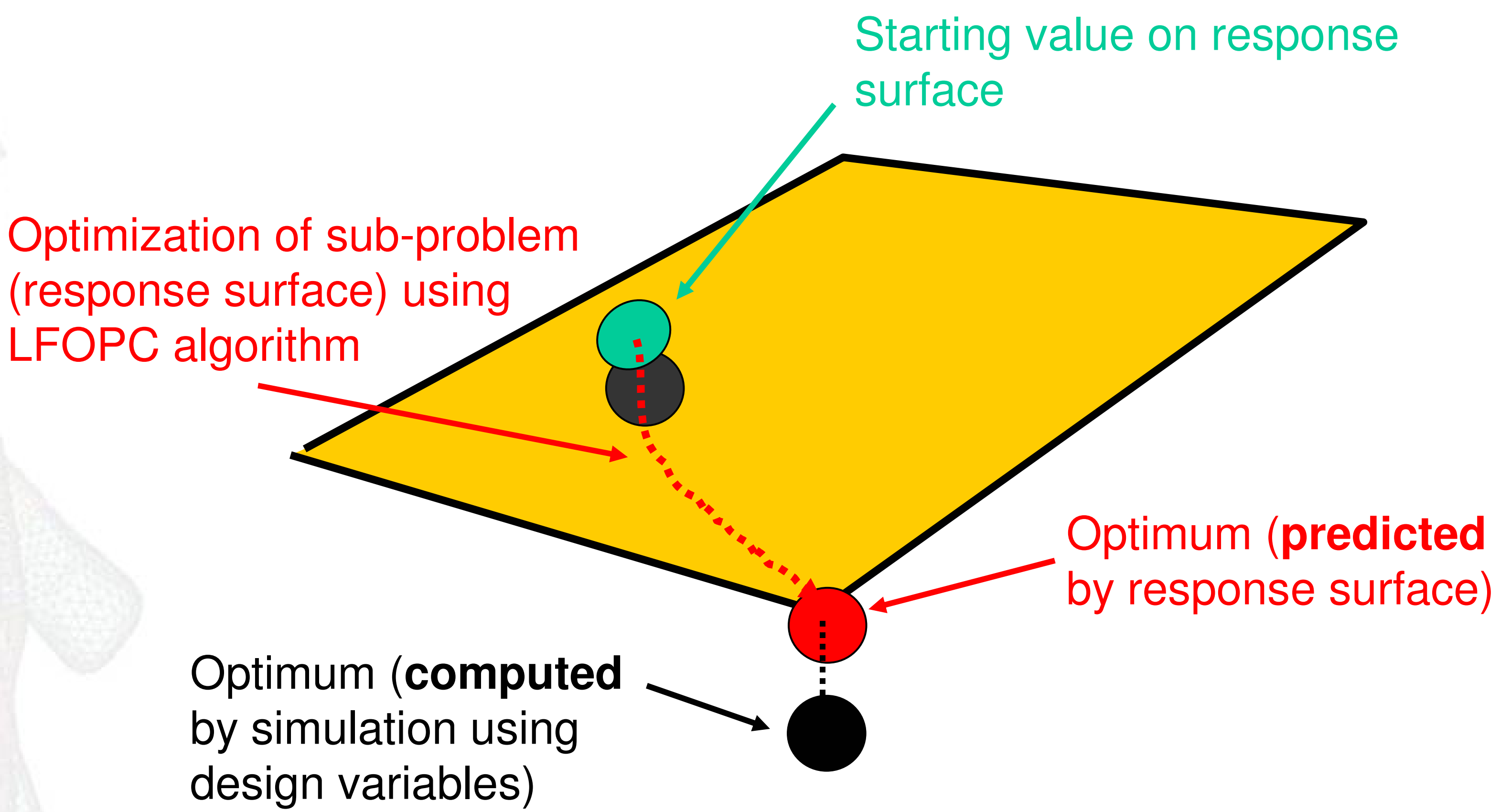
- Job Distribution - Interface to Queuing Systems
  - *PBS, LSF, LoadLeveler, AQS, etc.*
- LS-OPT might be used as a "Process Manager"
- Shape Optimization
  - *Interface to SFE-Concept, ANSA, HyperMorph, DEP-Morpher*
  - *User-defined interface to any Pre-Processor*
- Parameter identification module



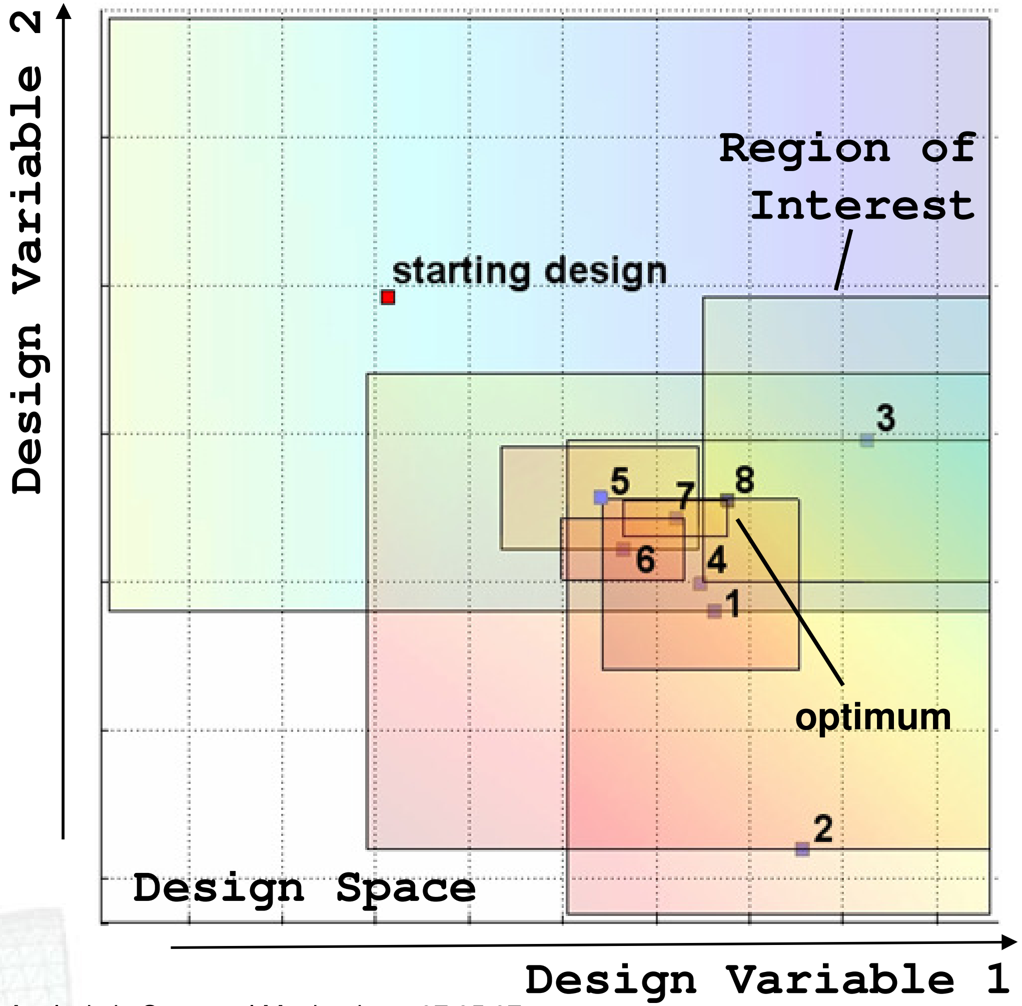
## ➔ Response Surface Methodology - Optimization Process



## ➔ Find an Optimum on the Response Surface (one iteration)



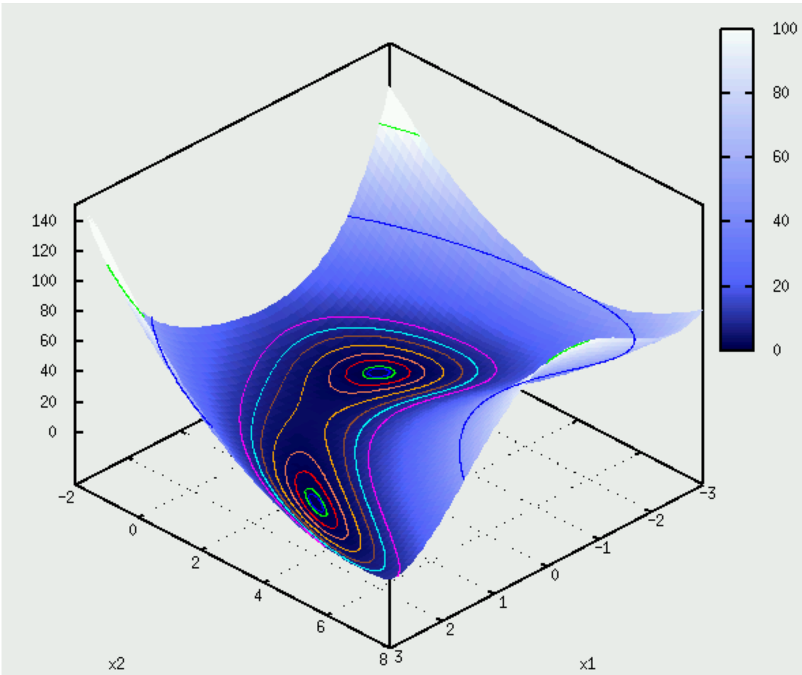
## ➔ Successive Response Surface Methodology



# ➔ Successive Response Surface Methodology

- Example - 4th order polynomial

$$g(\mathbf{x}) = 4 + \frac{9}{2}x_1 - 4x_2 + x_1^2 + 2x_2^2 - 2x_1x_2 + x_1^4 - 2x_1^2x_2$$

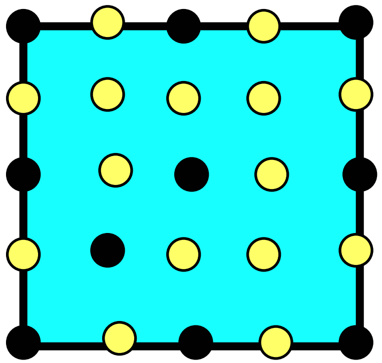



movie

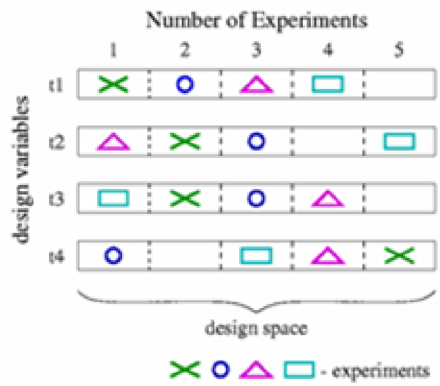
## → Design of Experiments (DOE) - Sampling Point Selection

- Koshal, Central Composite, Full Factorial
- D-Optimality Criterion - Gives maximal confidence in the model

$$\max \left| X^T X \right|$$

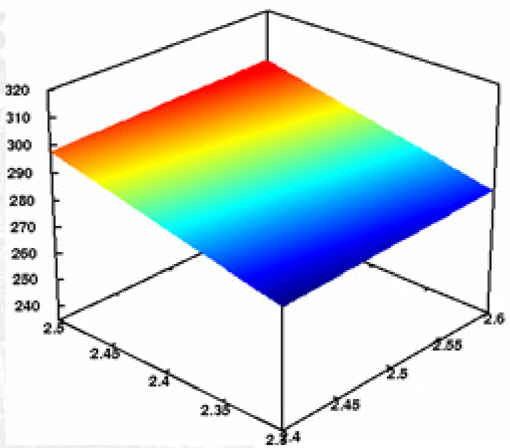


- Monte Carlo Sampling
- Latin Hypercube Sampling (stratified Monte Carlo)
- Space Filling Designs
- User Defined Experiments

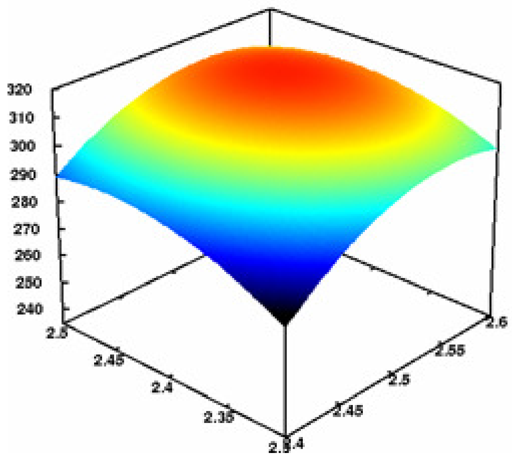


## ➔ Response Surfaces (Meta Models)

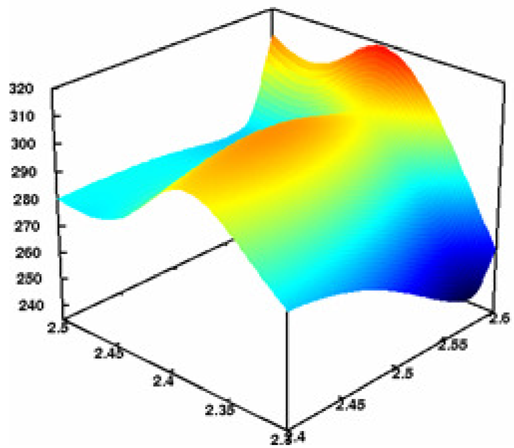
- Linear, Quadratic and Mixed polynomial based
- Neural Network and Kriging for Nonlinear Regression




**linear polynomial**




**quadratic polynomial**

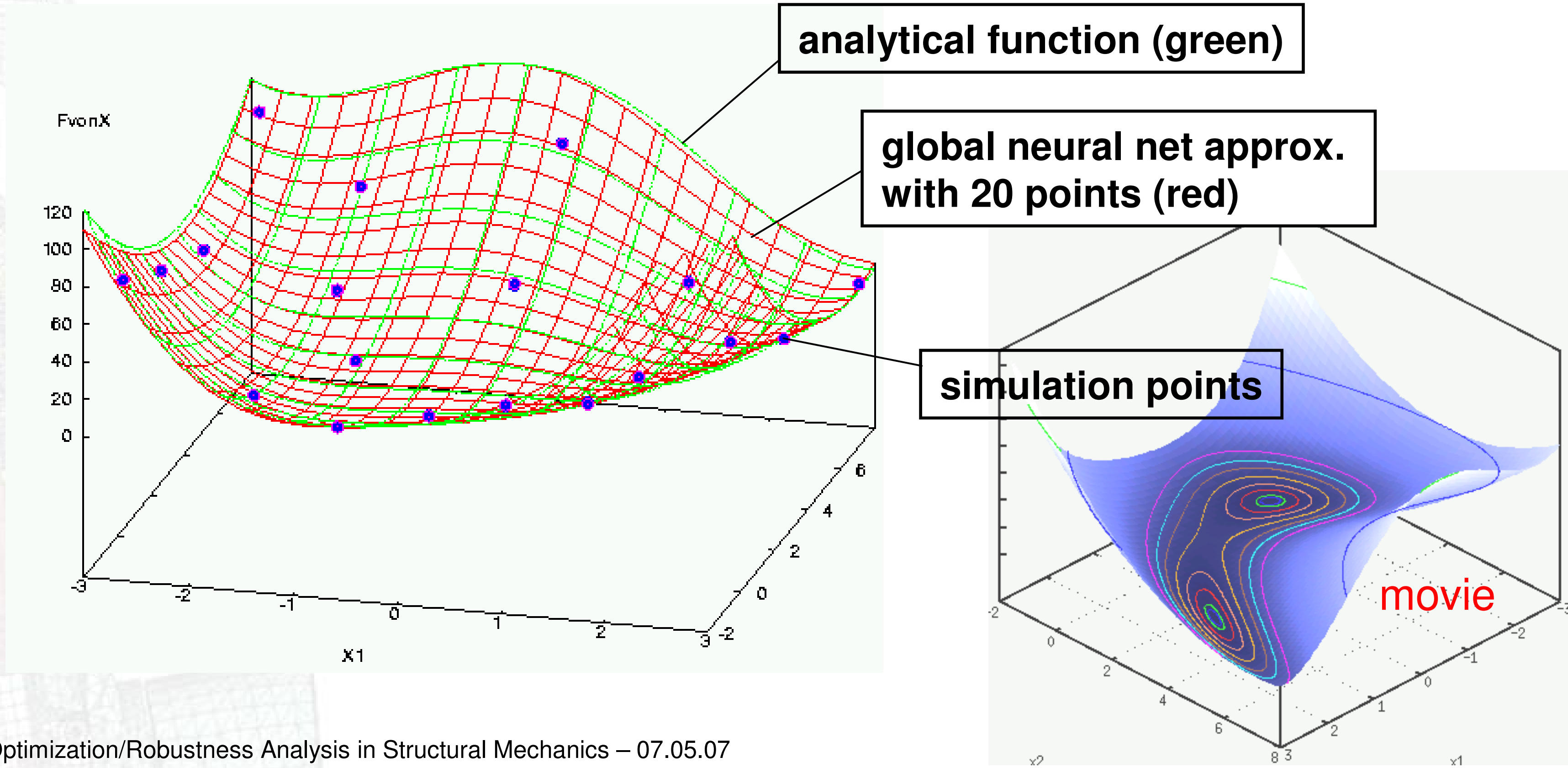



**neural network**

## ➔ Neural Network Regression

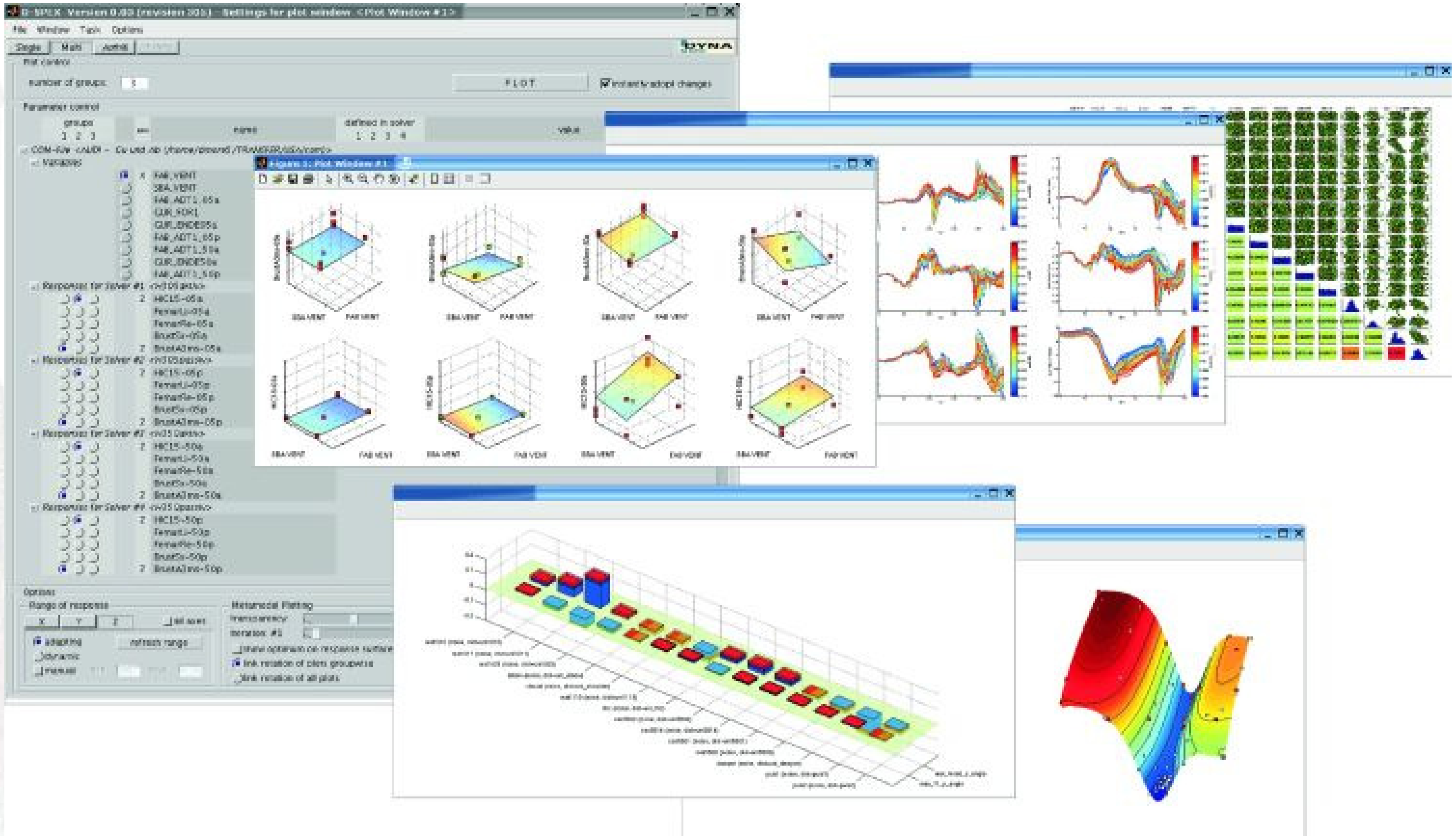
- Example - 4th order polynomial

$$g(\mathbf{x}) = 4 + \frac{9}{2}x_1 - 4x_2 + x_1^2 + 2x_2^2 - 2x_1x_2 + x_1^4 - 2x_1^2x_2$$



## ➔ Meta-Model Viewer - Exploration of Design Space

- Compare responses, histories or even different optimization projects

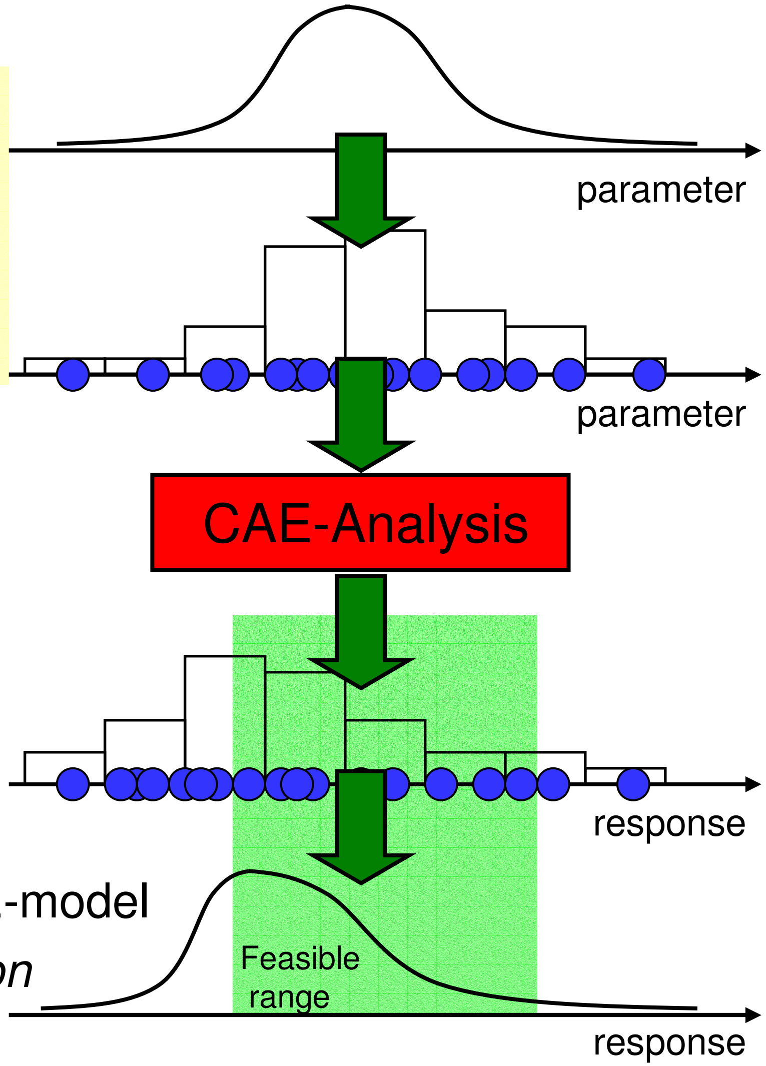


## → Overview – Optimization Methodologies for highly nonlinear Applications

| | *Gradient Based Methods* | *Random Search* | *Evolutionary Algorithms* | *RSM / SRSM* |
|---|---|---|---|---|
|  | ▪ accuracy of solution<br>▪ number of solver calls | ▪ very robust, can not diverge<br>▪ easy to apply | ▪ good for problems with many local minimas | ▪ very effective, particularly SRSM<br>▪ trade-off studies on RS<br>▪ filter out noise, smoothing of results |
|  | ▪ can diverge<br>▪ can stuck in local minimas<br>▪ step-size dilemma for numerical gradients | ▪ bad convergence, not effective<br>▪ Chooses best observation – may not be representative of a good (robust) design | ▪ many solver calls, only suitable for fast solver runs<br>▪ Chooses best observation – may not be representative of a good (robust) design | ▪ approximation error<br>▪ verification run might be infeasible<br>▪ number of variables control minimum number of required runs |

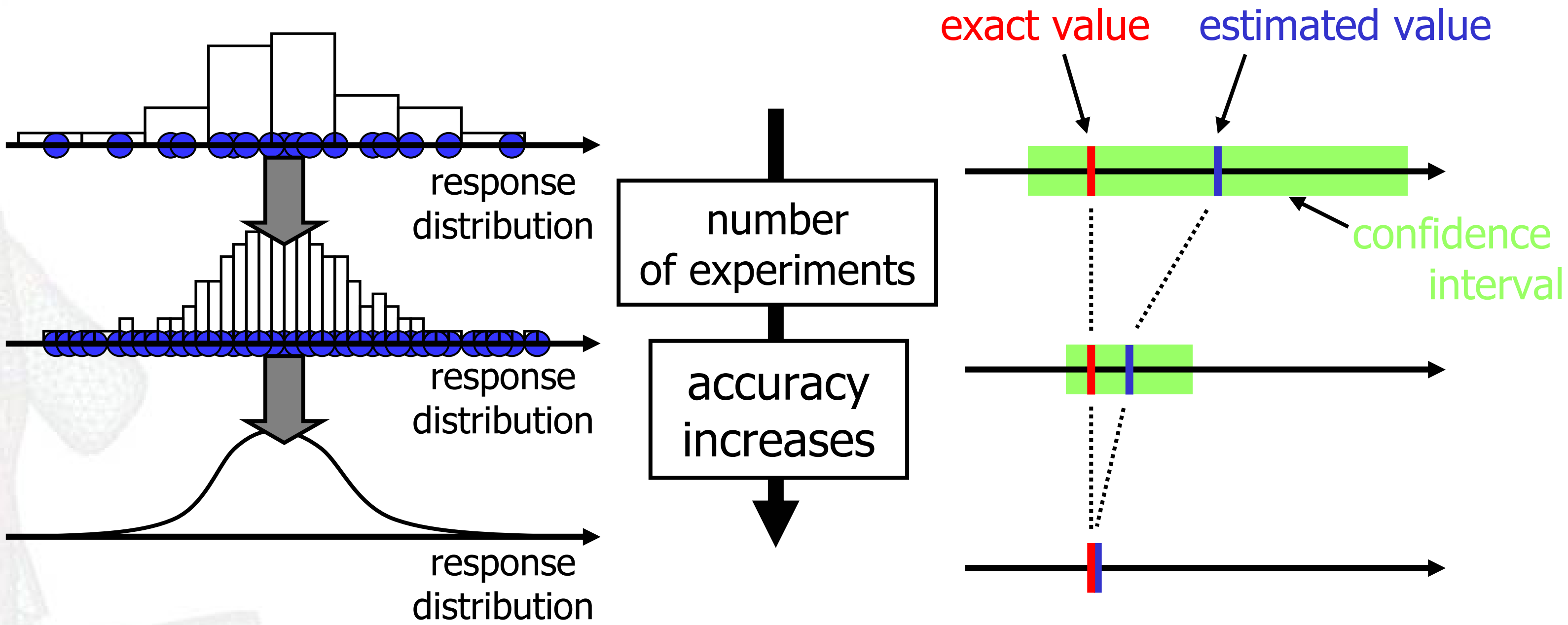
## ➔ Stochastic Analysis - Goals

- Statistical Quantities of Output (Response) due to Variation of Input (Parameter)
  - *Mean*
  - *Standard deviation*
  - *Distribution function*
- Significance of Parameter with respect to Responses
  - *Correlation analysis*
  - *Stochastic contributions*
  - *ANOVA – analysis of variance*
- Reliability Issues
  - *Probability of failure*
- Visualization of statistical quantities on FE-model
  - *Spatial detection of variation/correlation*



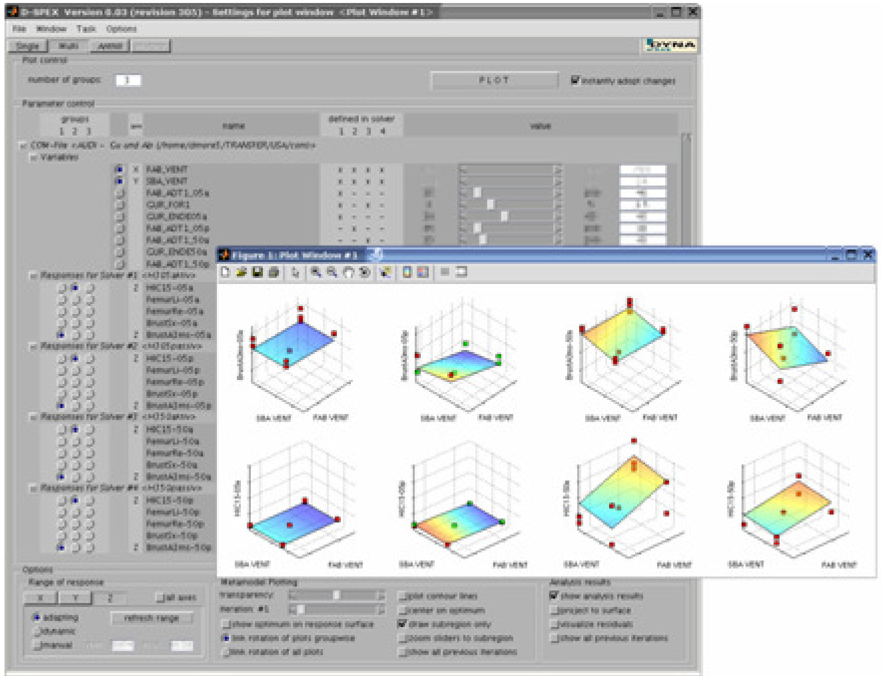
## ➔ Statistical Quantities of Output due to Variation of Input

- Direct Monte Carlo Sampling
  - *Latin Hypercube sampling*
  - *Large number of FE runs (100+)*
  - *Consideration of confidence intervals for mean, std. dev., correlation coeff.*



# ➔ Statistical Quantities of Output due to Variation of Input

- Monte Carlo using Meta-Models
  - *Response Surface / Neural Network*
  - *Medium number of FE runs (10 – 30+)*
  - *Number of runs depend on the dimension of the problem (number of variables) and the type of the response surface*
  - *Identify design variable contributions clearly*
  - *Exploration of parameter space ->D-SPEX*



**Multi Meta-Model exploration with D-SPEX**

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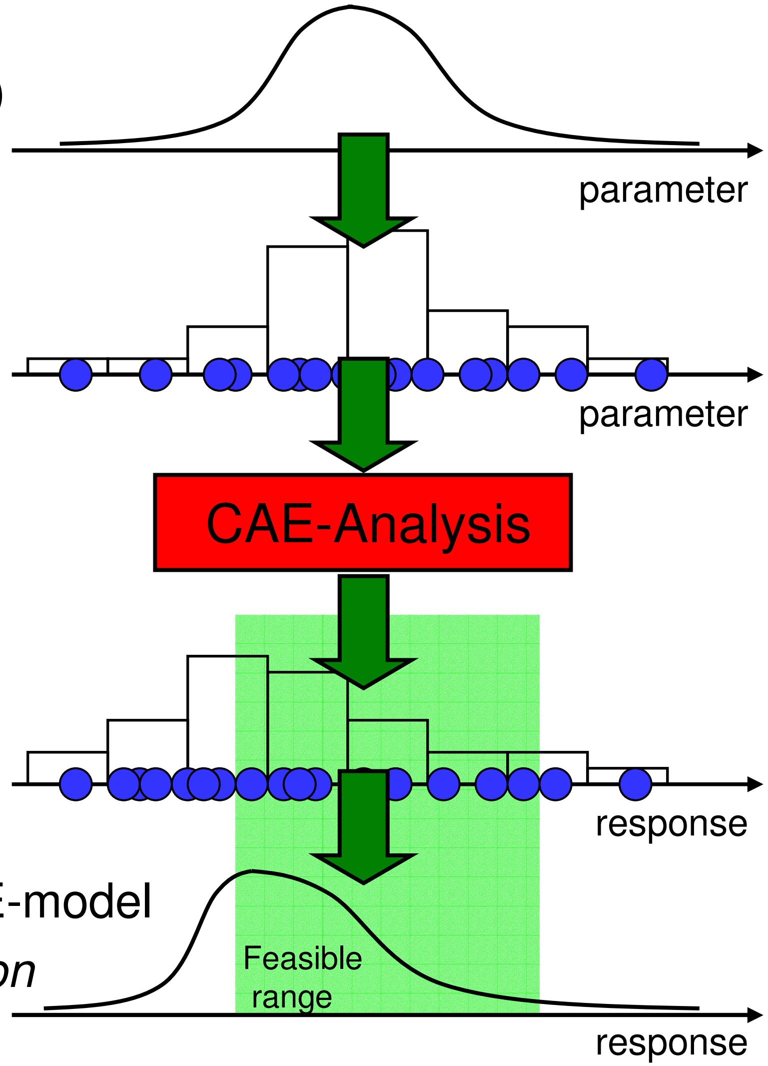
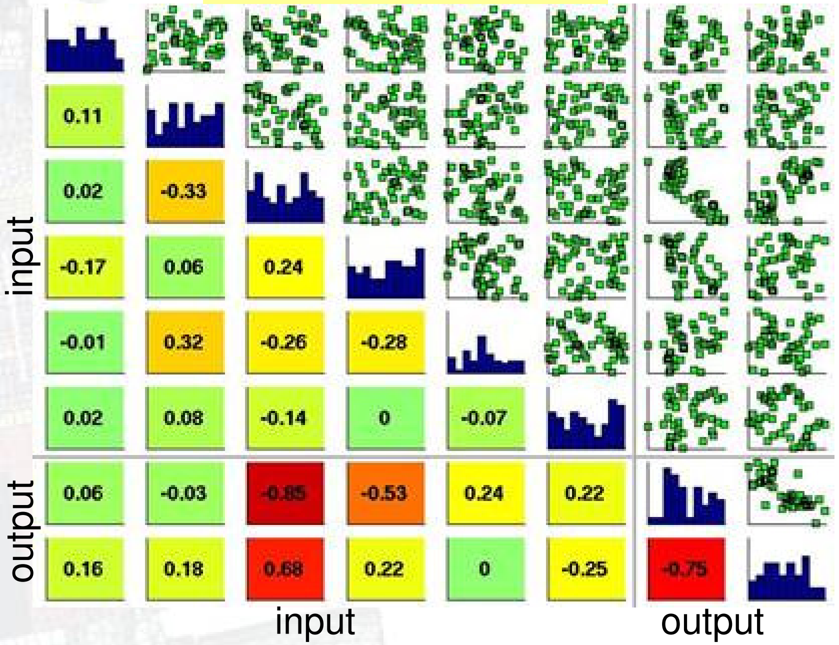
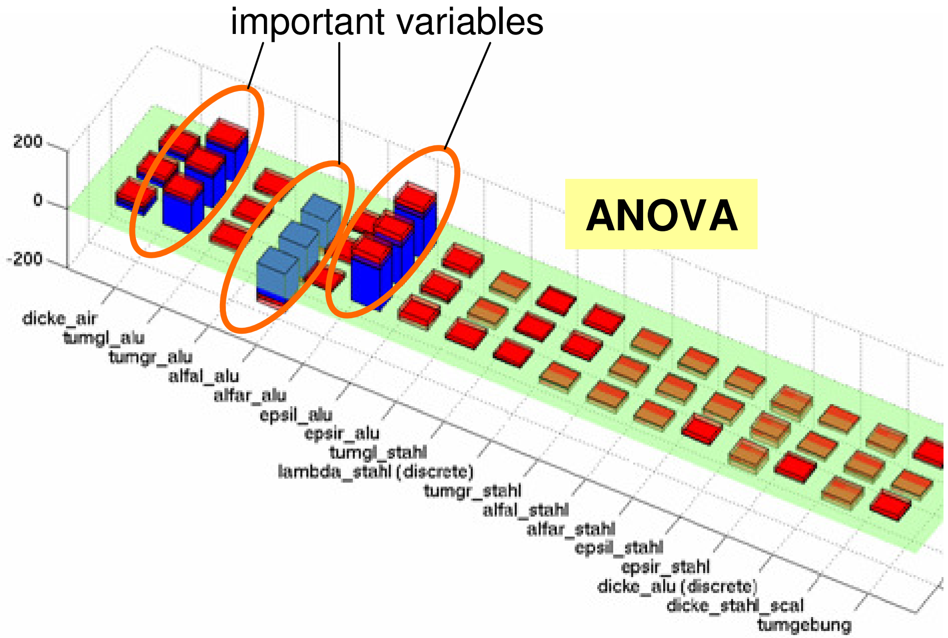


# ➔ Significance of Variables

- Correlation Analysis
- ANOVA - Meta-Model based
- Stochastic Contributions – Meta-Model based

**Correlation Matrix**



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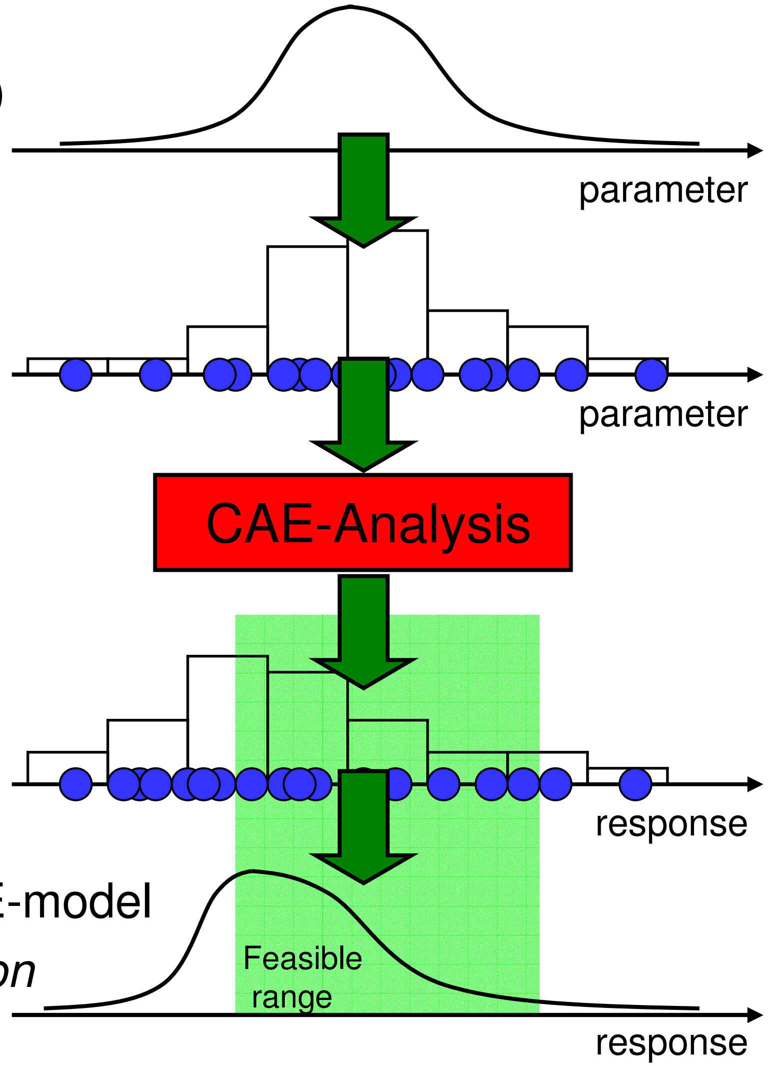
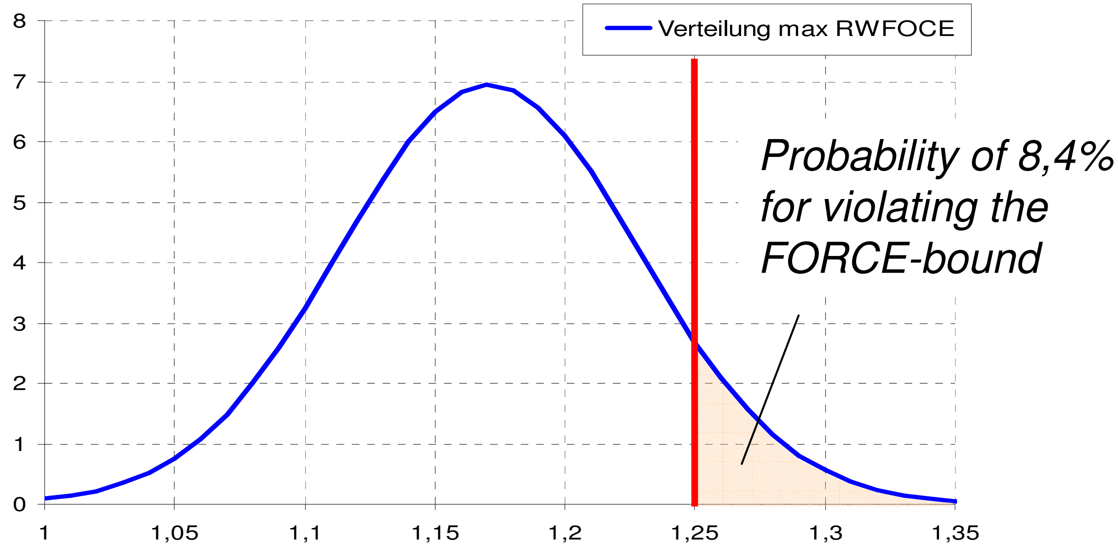


## ➔ Reliability Analysis

- Probability of failure
- Evaluation of confidence interval
- Prediction error (confidence interval) depends
  - *on the number of runs*
  - *on the probability of event*
  - ***not** on the dimension of the problem (number of design variables)*



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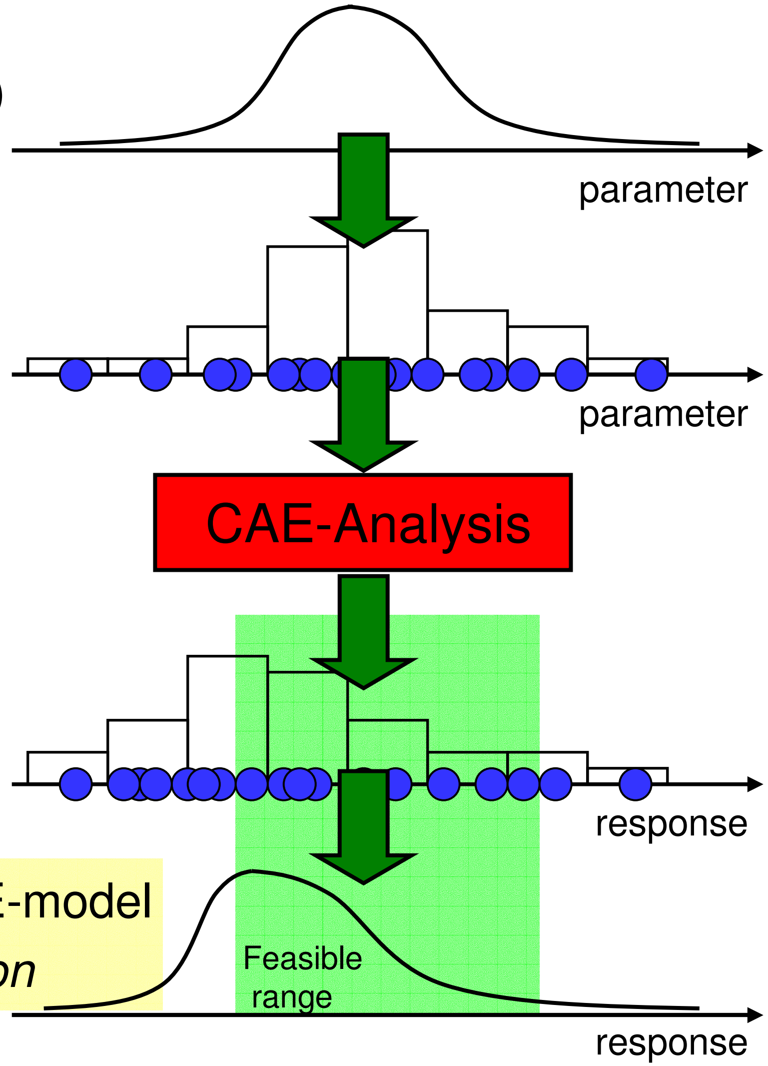
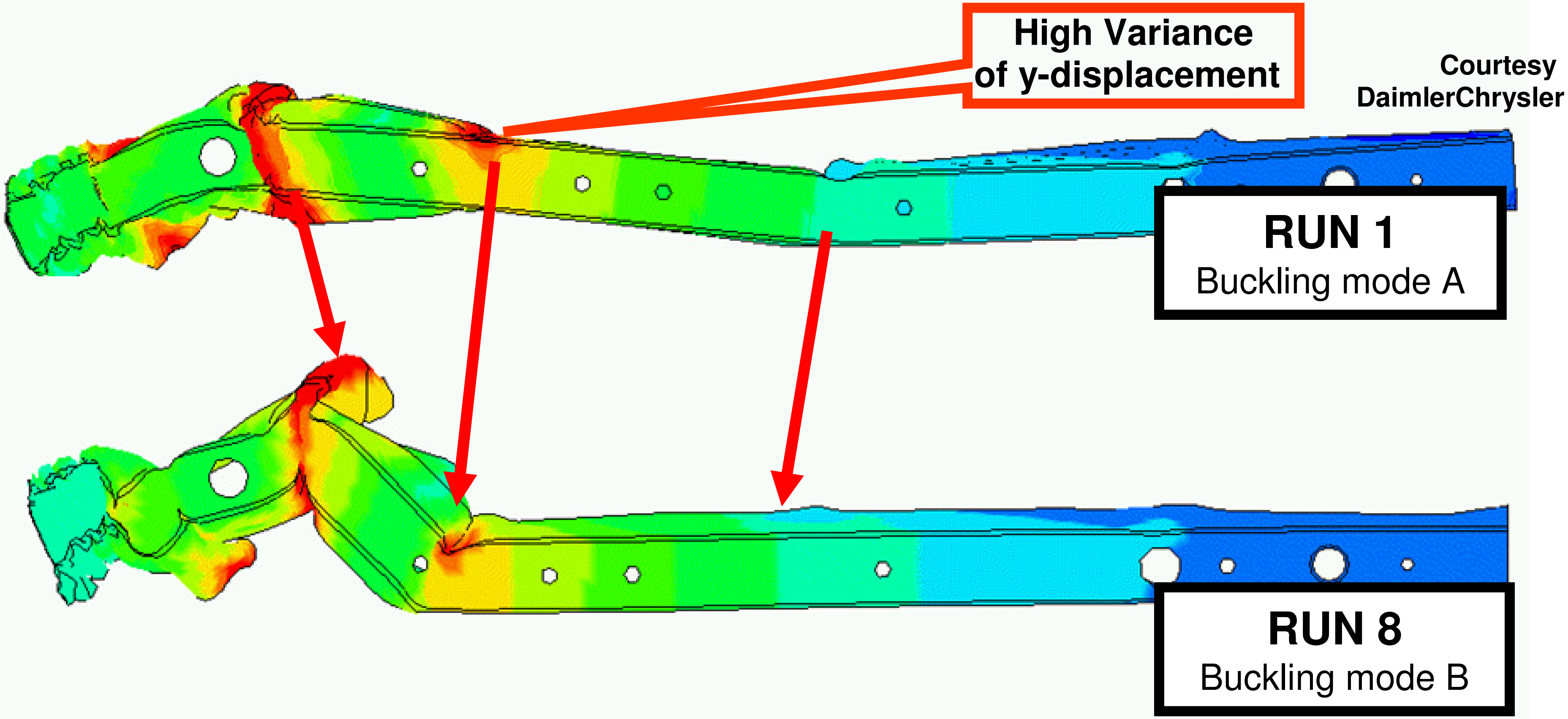


# ➔ Visualization of Statistical Quantities on FE-model

- Standard deviation of y-displacements of each node (40 runs)



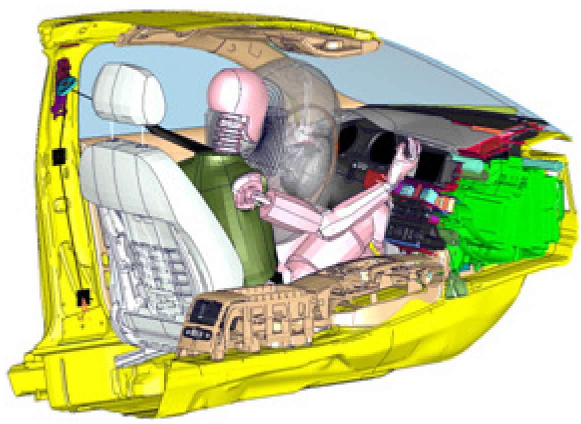
# Example I - Optimization

## ➔ Optimization of an Adaptive Restraint System

- Four Different Front-Crash Load Cases (FMVSS 208)

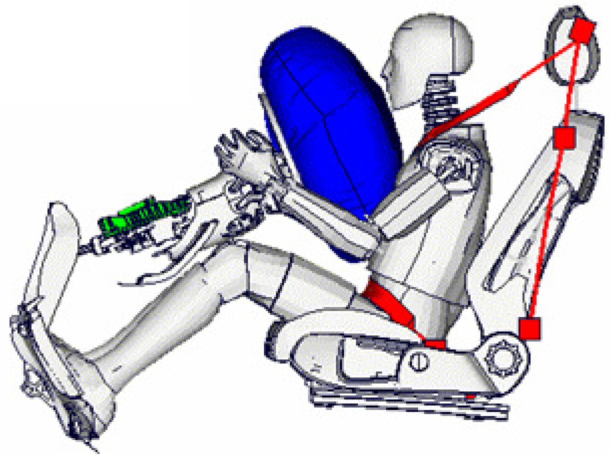
| Dummy | 56 km/h – belted | 40 km/h – not belted |
|---|---|---|
| Hybrid III 5th Female | **H305a**(ktiv) | **H305p**(assiv) |
| Hybrid III 50th Male | **H350a**(ktiv) | **H350p**(assiv) |

- PAM-Crash Model
  - *about 500000 elements*
  - *wall clock simulation time ~19 h, 4 cpus, distributed memory*
- Load Case Detection available
  - *Differentiation of the loadcases* ***belted*** */* ***not belted*** *and* ***"Hybrid III 5th Female"*** */* ***„Hybrid III 50th Male"*** *possible*
  - *Trigger time for seatbelt, airbag and steering column might be different*



# Example I - Optimization

## ➔ Optimization Problem



- Objective
  - *Minimize Thorax Acceleration*

    -> min BrustA3ms-05a
    -> min BrustA3ms-50a
    -> min BrustA3ms-05p
    -> min BrustA3ms-50p

- Constraints < 80% of regulation requirements
  - *Head Injury Coefficient (15ms)*

    -> HIC15-05a
    -> HIC15-50a
    -> HIC15-05p
    -> HIC15-50p
  - *Thorax Intrusion*

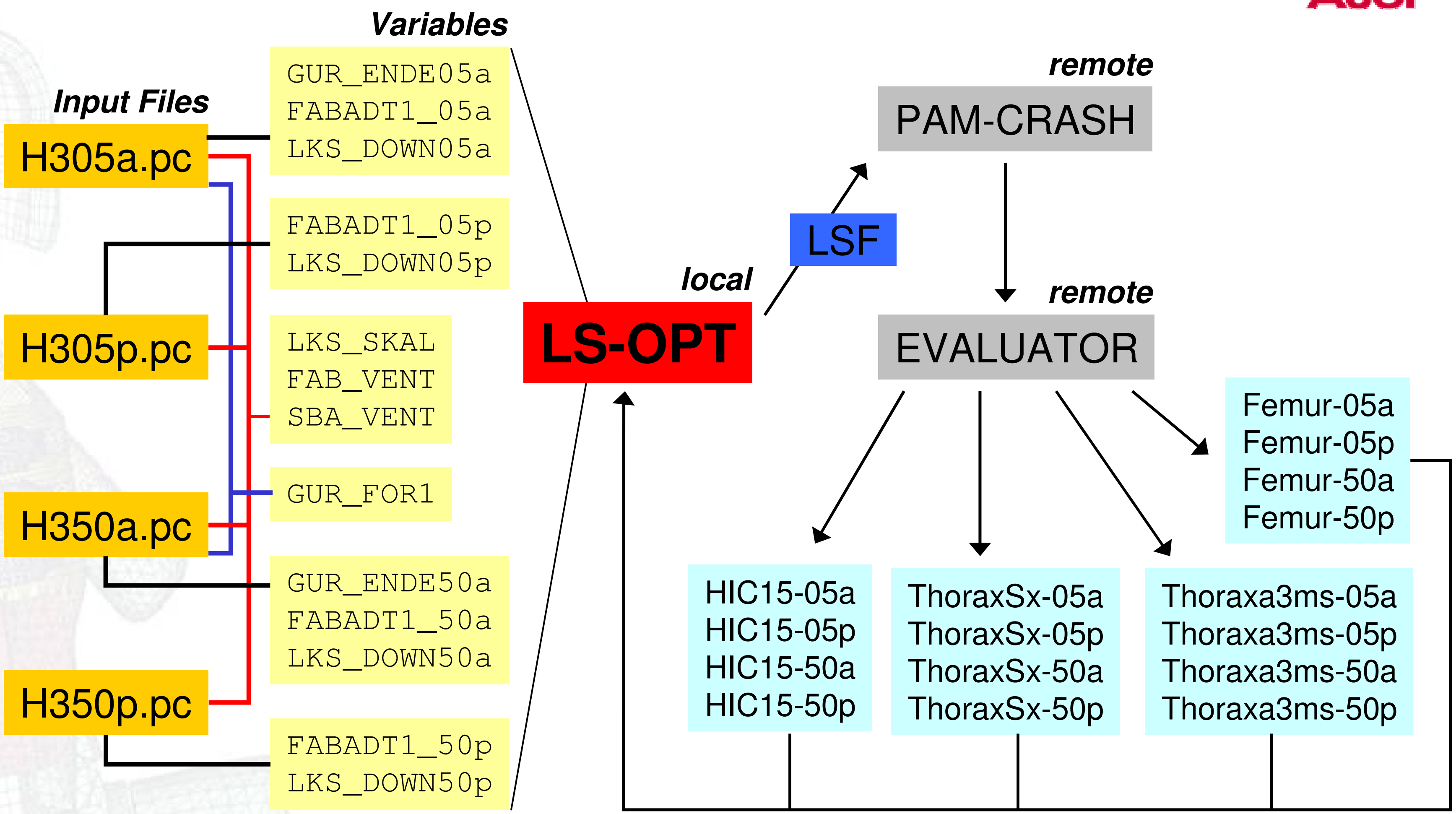
    -> BrustSx-05a
    -> BrustSx-50a
    -> BrustSx-05p
    -> BrustSx-50p
  - *Femur Forces (left/right)*

    -> FemurLi-05a
    -> FemurLi-50a
    -> FemurLi-05p
    -> FemurLi-50p
  - *Thorax Acceleration*

    -> BrustA3ms-05a
    -> BrustA3ms-50a
    -> BrustA3ms-05p
    -> BrustA3ms-50p

# Example I - Optimization

## ➔ Process Work Flow



# Example I - Optimization



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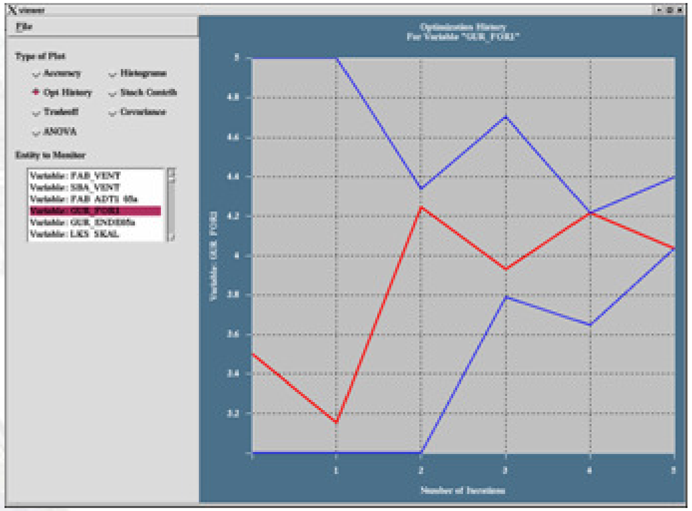
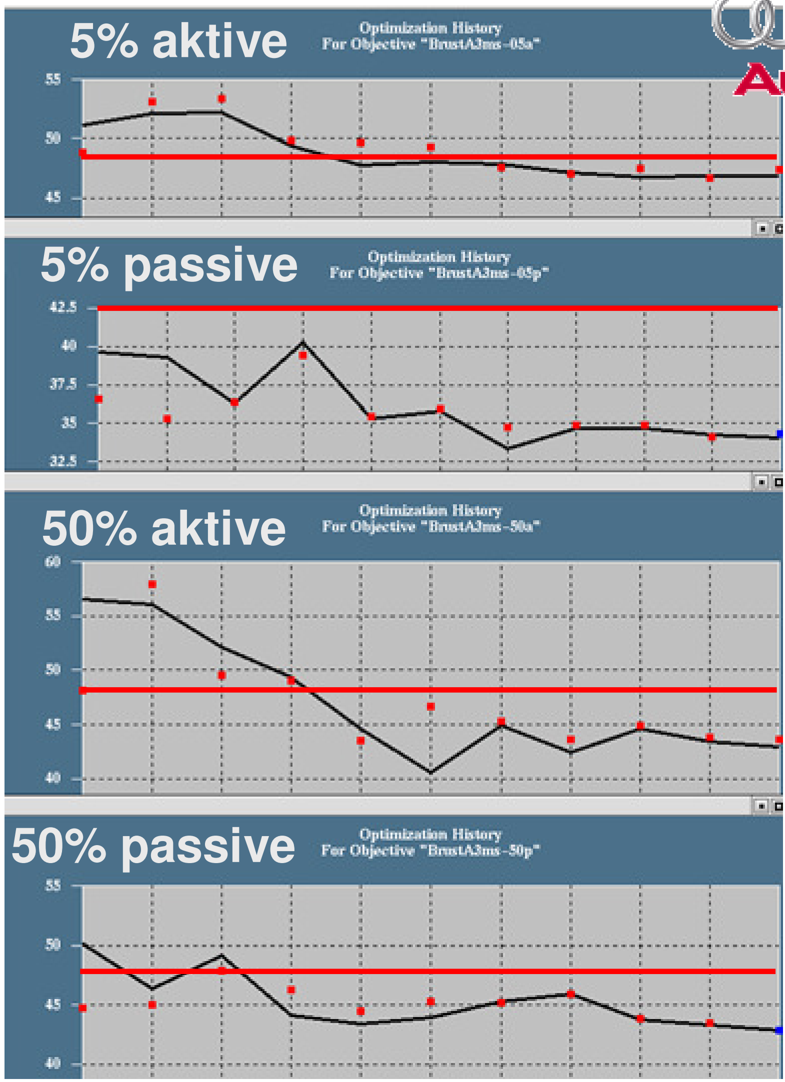
## ➔ Results




Deployment of variable **`Belt_Force`**

a result which meets all requirements is gained in 8 iterations, each with 34 shots

History of Thorax Acceleration

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# Example I - Optimization

## ➔ Parameter Identification of Plastic Material

- Material properties: nonlinear visco-elastic behaviour
- LS-DYNA hyperelastic/viscoelastic formulation - *MAT_OGDEN_RUBBER (#77)
- Hyperelasticity

$$W = \sum_{i=1}^{3} \sum_{j=1}^{n} \frac{\mu_j}{\alpha_j}\left(\lambda_i^{\alpha_j} - 1\right) + \frac{1}{2} K (J-1)^2$$

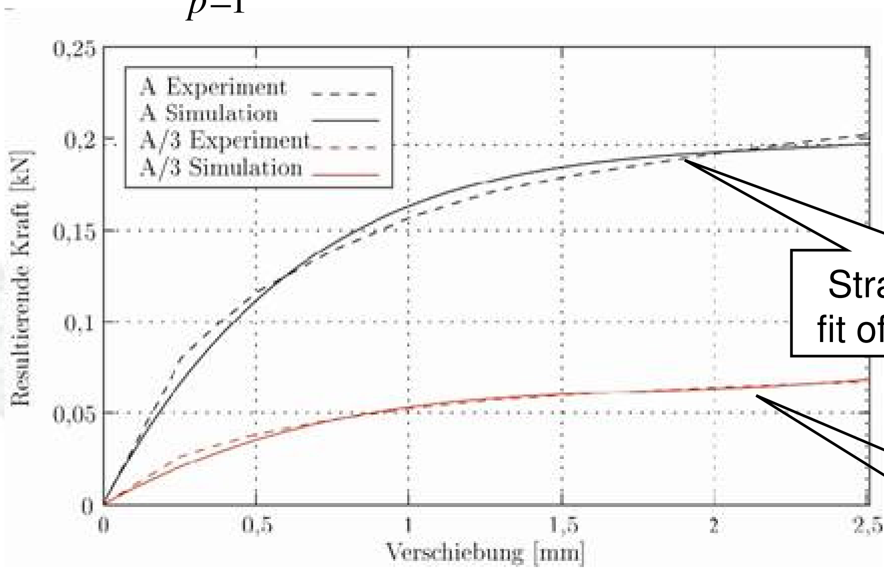
- Prony series representing the viscos-elastic part (Maxwell elements):

$$g(t) = \sum_{m=1}^{N} G_m e^{-\beta_m t} \quad ; \; \text{N=1, 2, 3, 4, 5, 6} \quad ; \; \sigma_{ij} = \int_0^t g_{ijkl}(t-\tau) \frac{\partial \varepsilon_{kl}}{\partial \tau} d\tau$$

## ➔ Parameter Identification of Plastic Material

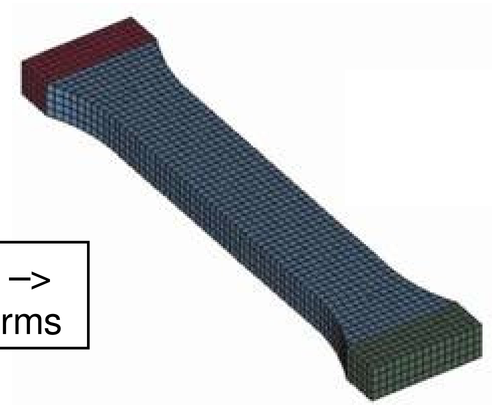
- Minimize the distance between experimental curve and simulation curve
- Least-Squares Objective Function

$$F(\mathbf{x}) = \sum_{p=1}^{P} \{[y(\mathbf{x}) - f(\mathbf{x})]^2\} \;\rightarrow\; \min F(\mathbf{x})$$



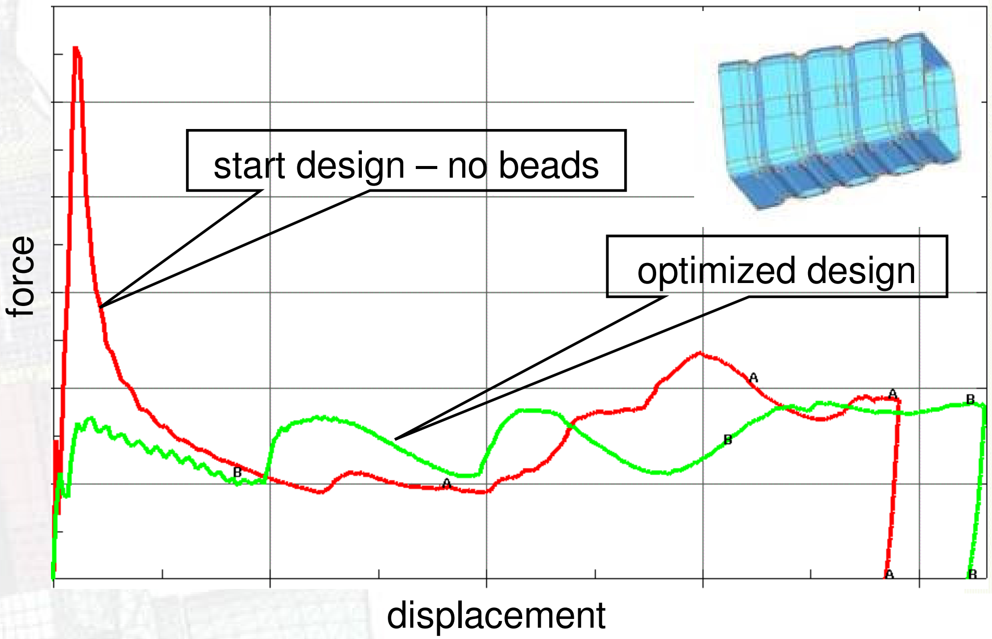

Strain rate A –> fit of Prony terms

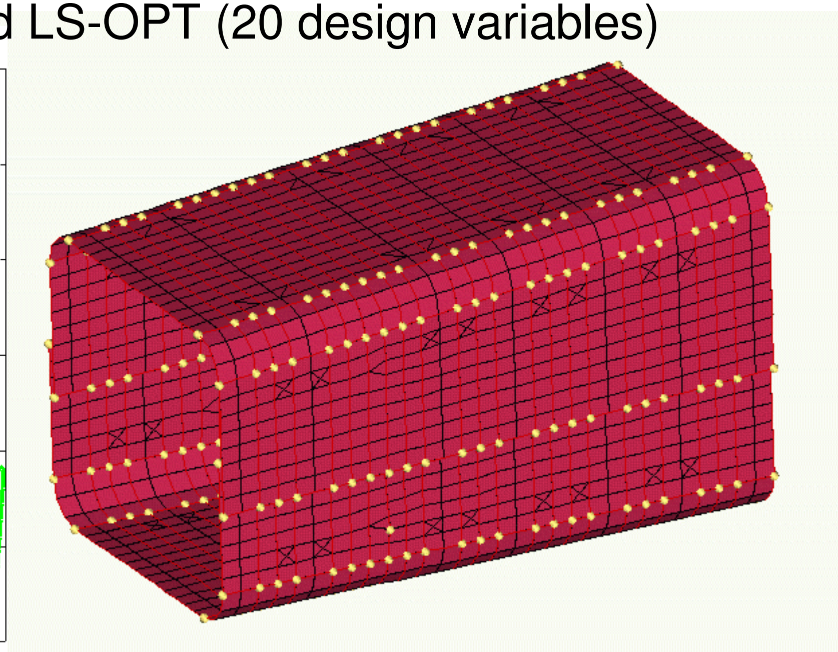
quasi-static curve –> Ogden fit



## ➔ Shape Optimization of a Crash Box

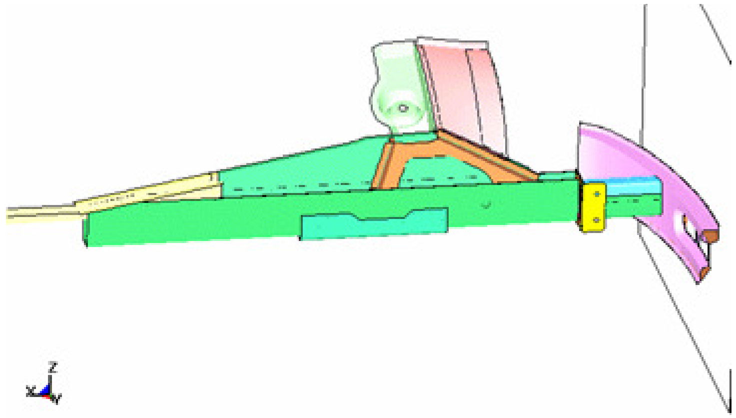
- Scope of optimization:
  - *minimize the maximum crash force*
  - *steady-going force progression*
- Shape variation by using Hypermorph and LS-OPT (20 design variables)



## ➔ Robustness Investigations – Monte Carlo Analysis

- Variation of sheet thicknesses and yield stress of significant parts in order to consider uncertainties
- Normal distribution is assumed
  - *T_1134 (Longitudinal Member)* *mean = 2.5mm;* *σ = 0.05mm*
  - *T_1139 (Closing Panel)* *mean = 2.4mm;* *σ = 0.05mm*
  - *T_1210 (Absorbing Box)* *mean = 0.8mm;* *σ = 0.05mm*
  - *T_1221 (Absorbing Box)* *mean = 1.0mm;* *σ = 0.05mm*
  - *SF_1134 (Longitudinal Member)* *mean = 1.0 ;* *σ = 0.05*
- Monte Carlo analysis using 182 points (Latin Hypercube)

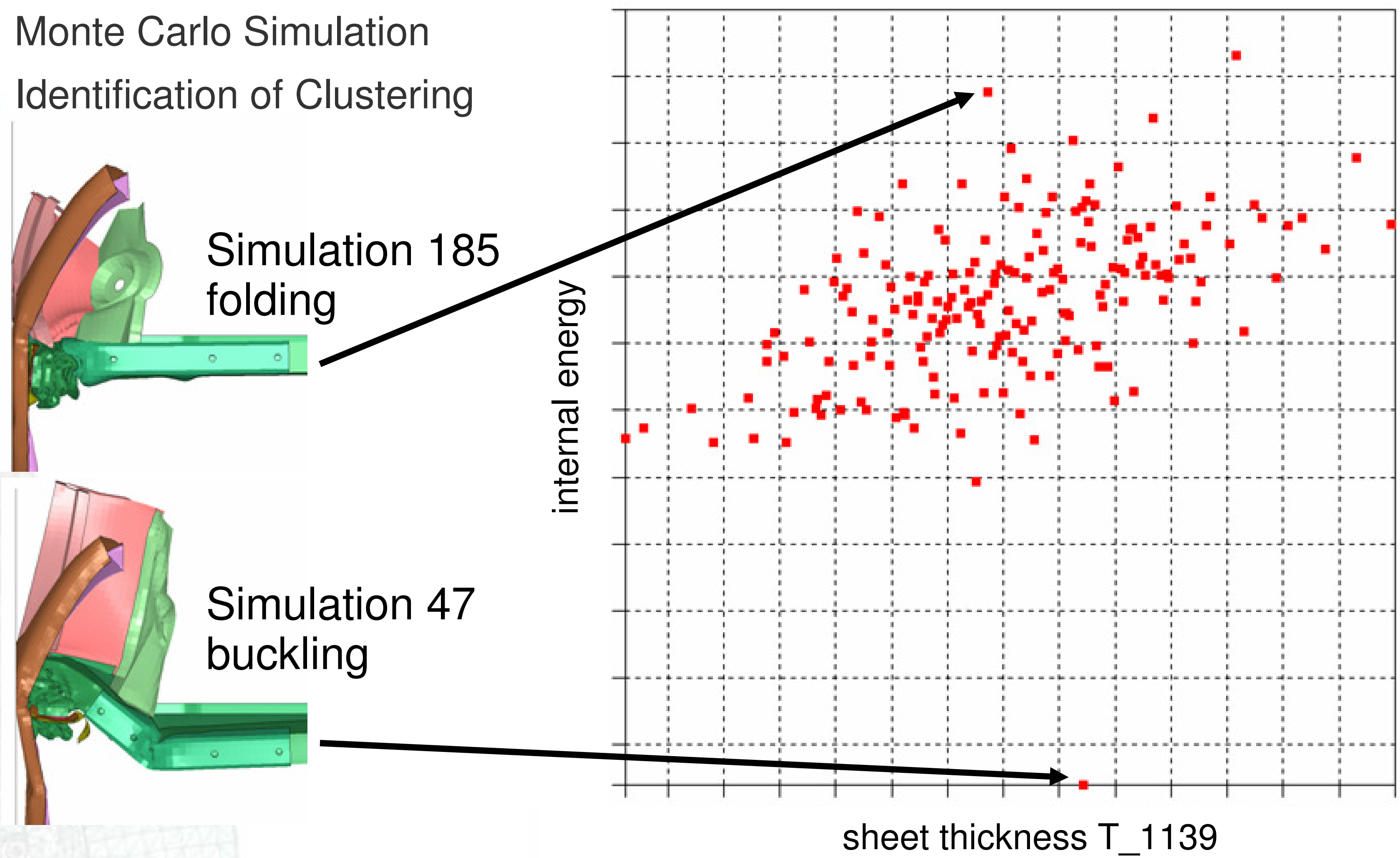


# Example I – Robustness



## ➔ Tradeoff Plot

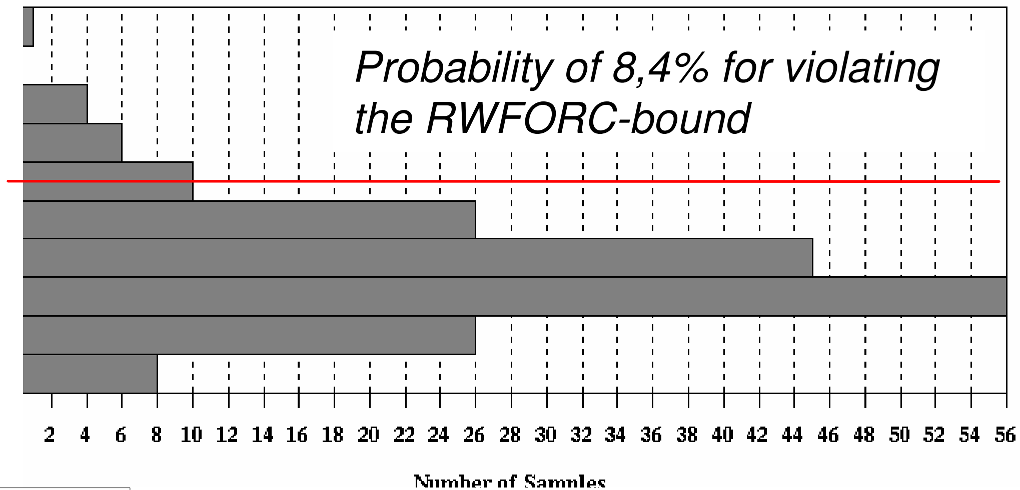
- Monte Carlo Simulation
- Identification of Clustering



# Example I – Robustness

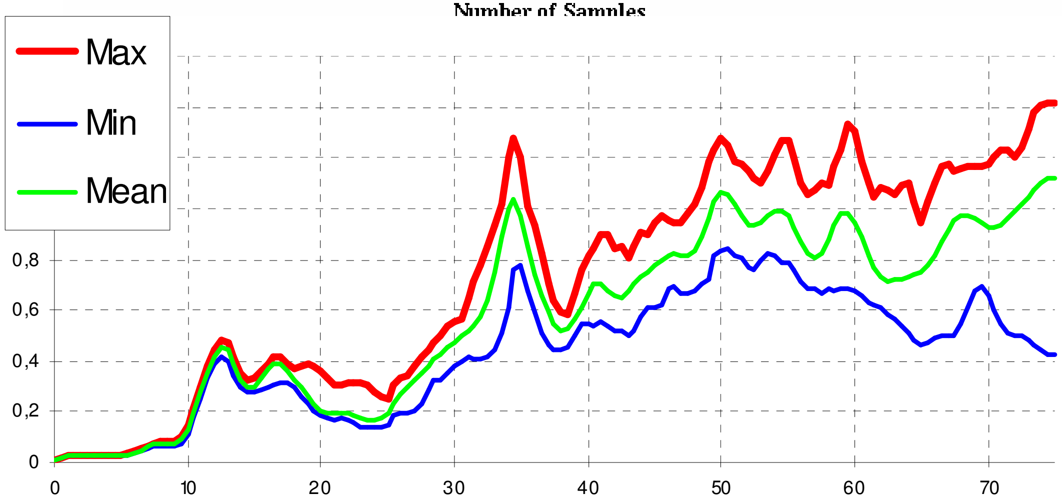
## ➔ Reliability Analysis

- Histogram of distribution
- Probability of exceeding a constraint-bound



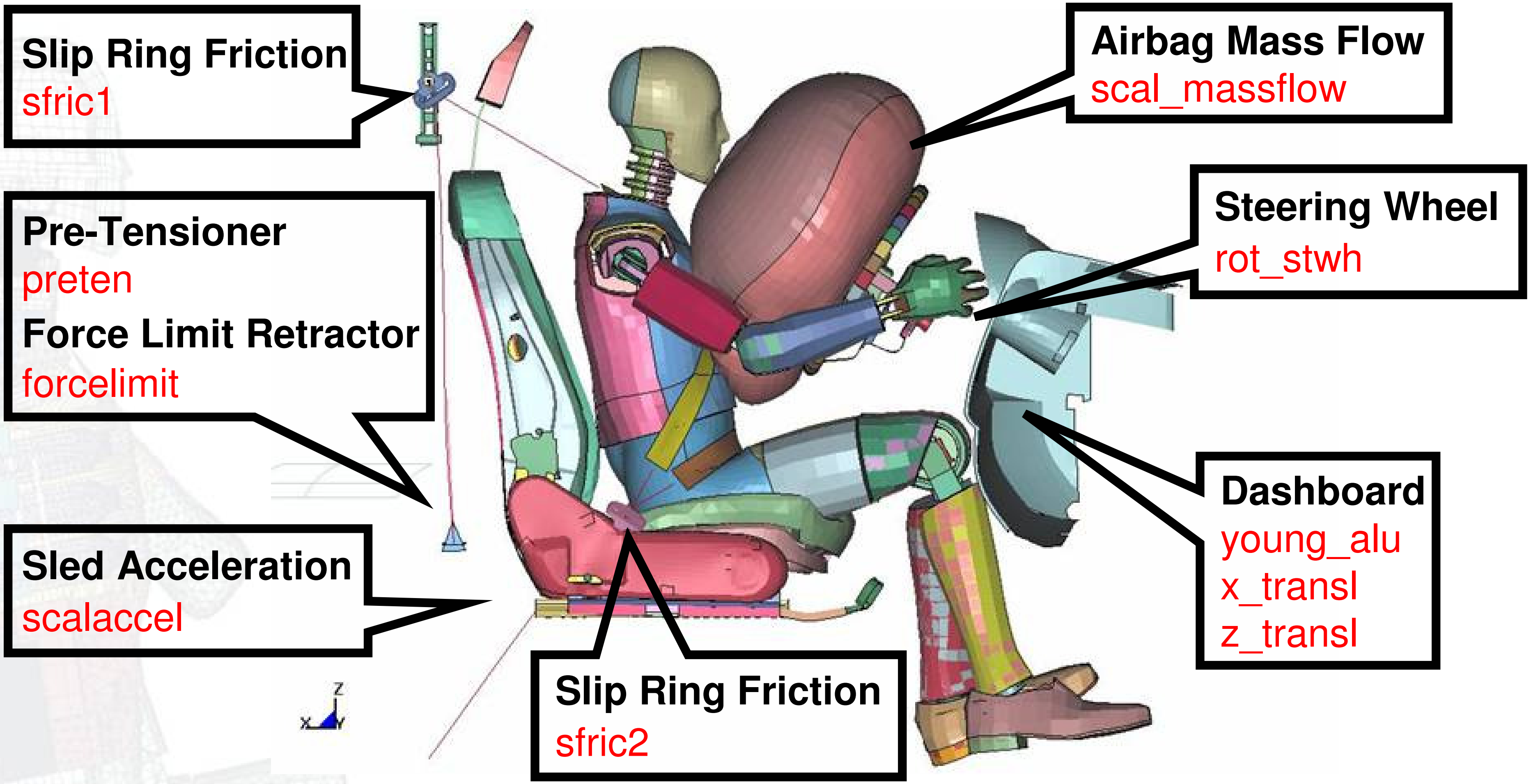

## ➔ Min-Max Curves

- Plot of minimum, maximum and mean history values
- Gives a confidence interval of history values



# Example II – Robustness

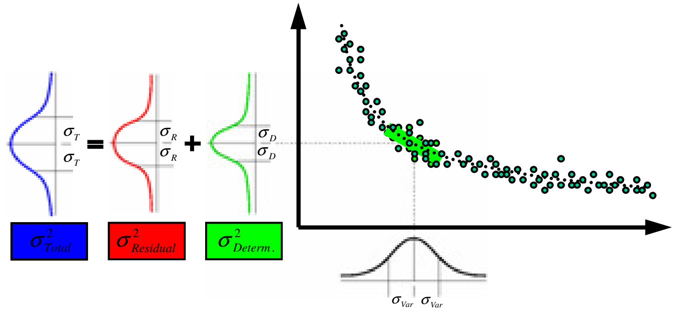
## ➔ Design Variables - Uncertainties in Test Set-Up



# Example II – Robustness

## ➔ Stochastic Contribution - Results of 30 Experiments

| Design Variable | Standard Deviation of Design Variable | Standard Deviation Contribution HIC36 | max_chest_intru | max_b_f_shoulder | max_bf_pelvis | max_chest | max_pelvis |
|---|---|---|---|---|---|---|---|
| scalaccel | 2,5% | 3,1% | 1,5% | 0,1% | 2,3% | 1,9% | 2,9% |
| sfric1 | 25,0% | 1,3% | 0,6% | 4,1% | 1,8% | 0,7% | 0,7% |
| sfric2 | 25,0% | 0,5% | 0,6% | 0,1% | 3,7% | 0,1% | 0,1% |
| preten | 4,4% | 0,0% | 0,5% | 0,0% | 1,1% | 0,3% | 0,2% |
| forcelimit | 5,6% | 1,3% | 0,4% | 4,4% | 0,6% | 1,4% | 0,2% |
| rot_stwh | 4,8% | 0,5% | 0,1% | 0,1% | 0,0% | 0,1% | 0,1% |
| transl_x | 50,0% | 0,1% | 0,1% | 0,7% | 4,5% | 0,5% | 0,8% |
| transl_z | 50,0% | 1,2% | 1,0% | 0,3% | 1,6% | 0,2% | 0,9% |
| scalmassflow | 5,0% | 1,8% | 1,8% | 0,6% | 2,2% | 0,6% | 0,9% |
| young_alu | 5,0% | 0,3% | 0,3% | 0,0% | 0,5% | 0,1% | 0,1% |
| all variables | | 4,3% | 2,8% | 6,1% | 7,2% | 2,6% | 3,4% |
| residuals | | 4,7% | 1,9% | 1,8% | 6,0% | 3,5% | 2,3% |
| **Total** | | **6,4%** | **3,4%** | **6,3%** | **9,4%** | **4,3%** | **4,1%** |




**Contribution of**
variation of design variables to variation of results

Meta-model space

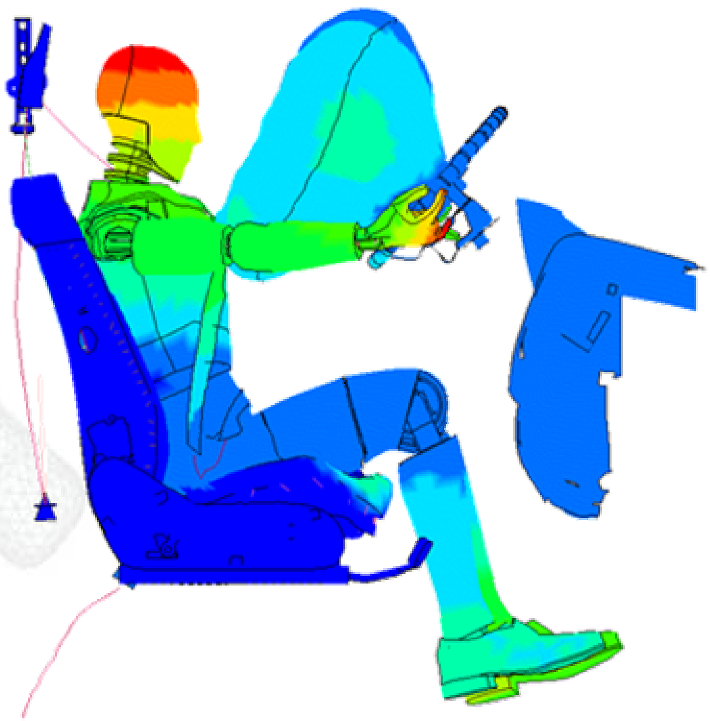
Residual space

Total Variation

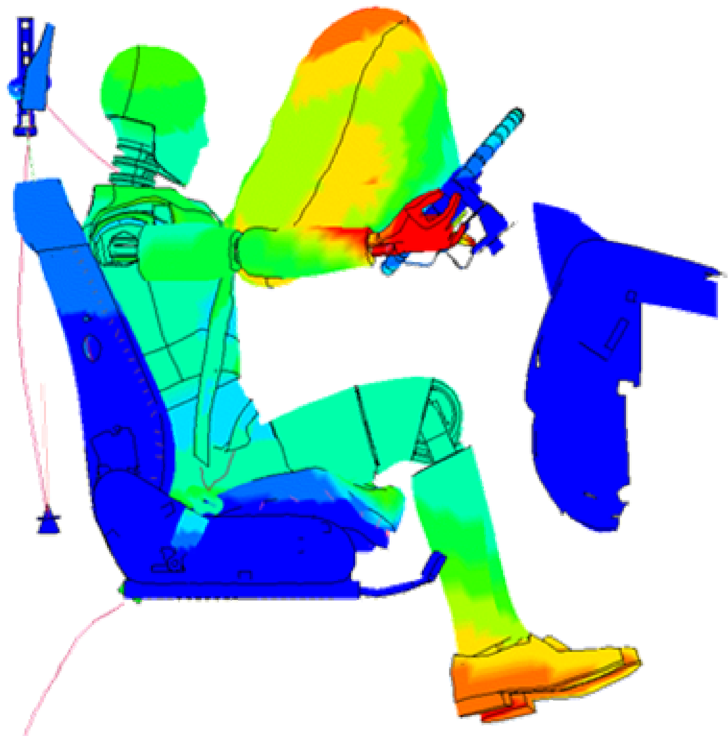
# Example II – Robustness

➔ **Standard deviation of x-displacements of each node (120 runs)**

(a) Deterministic (Meta-Model)

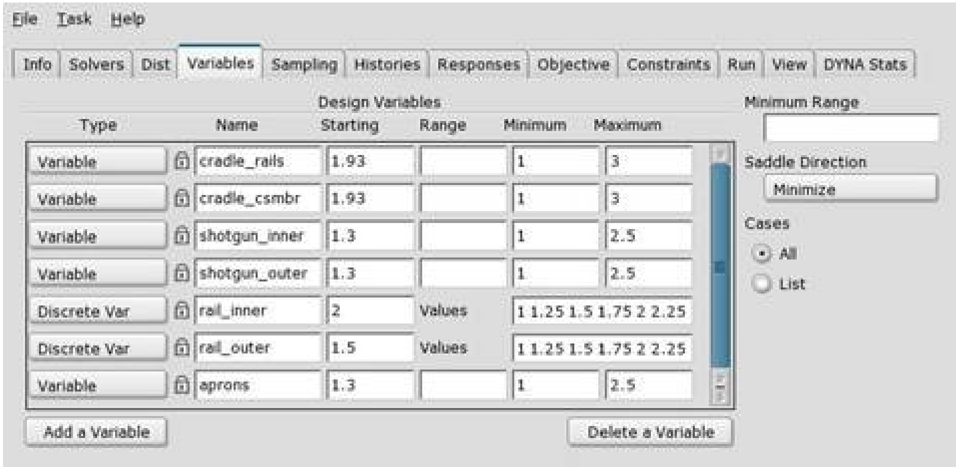


(b) Residual (Outliers)



# ➔ Version 3.2

- Mixed Discrete-Continous Optimization
  - *Specify sets of variables (e.g. sheet thicknesses)*
  - *Not really suitable for strong discrete values, e.g. variation of material models (combinatorial problem)*

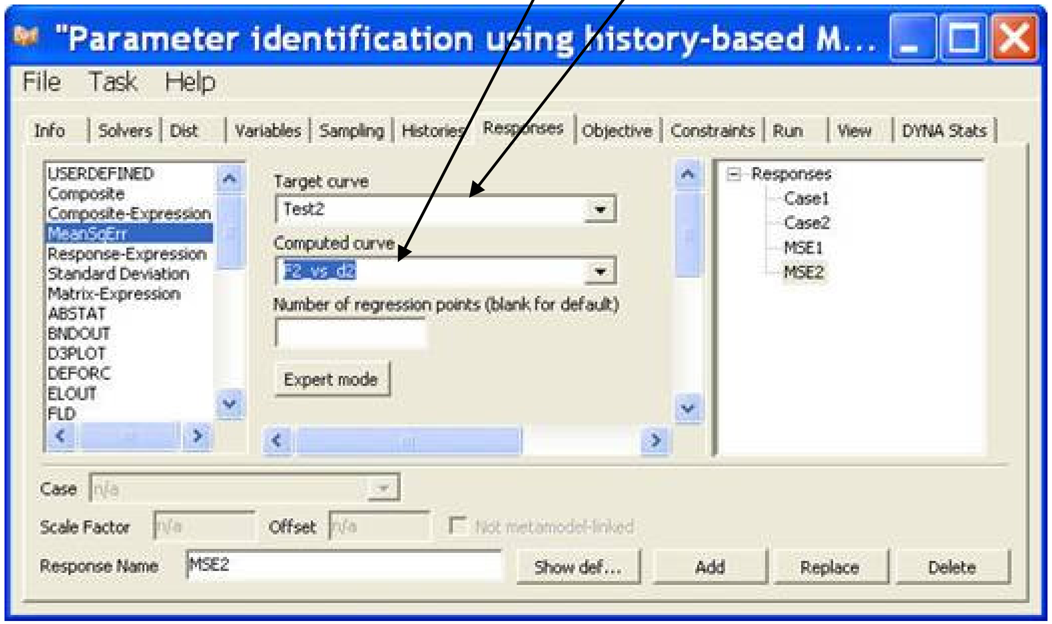



- Robust Parameter Design
  - *Improve/Maximizing the robustness of the optimum*
- Improved Visualization of Stochastic Results
  - *Confidence Intervals, reliability quantities*

## ➔ Version 3.2

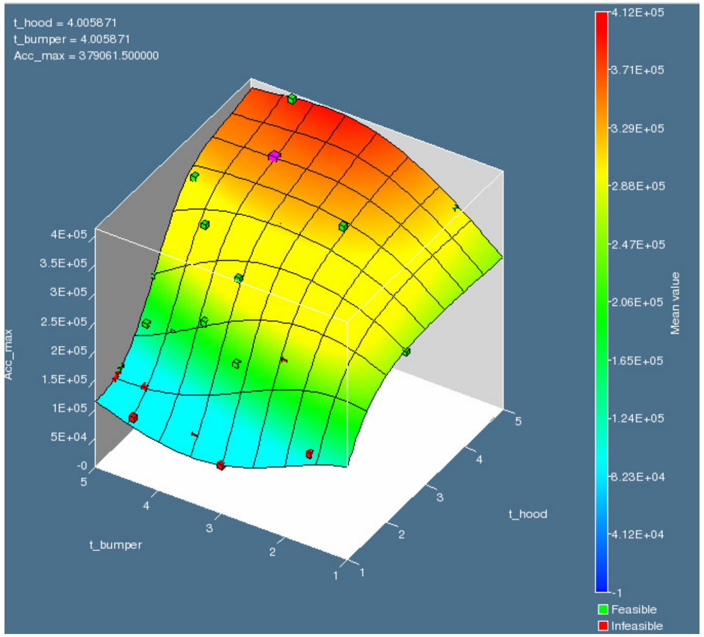
- Parameter Identification Module
  - *Handles "continuous" test curves*
  - *Automated use of test results to calibrate materials/systems*
  - *Simplify input for system identification applications*
  - *Visualization of test and simulation curve to compare*

$$\frac{1}{P}\sum_{p=1}^{P} W_i \left( \frac{F_i(\mathbf{x}) - G_i}{s_i} \right)^2$$



## Version 3.2

- 3-D Plotting of Meta-Models
  - *Analysis result points added*
- Data compression
  - *d3plot files*
- Checking of output requests
  - **DATABASE cards, node numbers*
- Job distribution
  - *Retry of failed queuing*
  - *Third case: "Abnormal Termination"*



## → Next Steps – Version 3.3 (late 2007)

- Additional injury criteria
  - *IIHS, neck/tibia indices, NCAP*
- User-defined Meta Model
- Picture formats
  - *e.g. .jpg, .tiff, etc.*
- ANOVA chart enhancements
  - *Add Confidence intervals for individual parameters in parameter identification (GUI only)*

## ➔ Next Steps – Version 3.3 (late 2007)

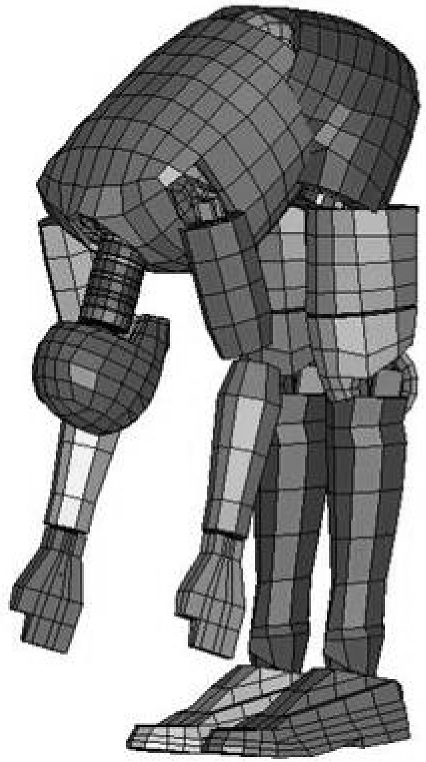
- Enhancements to Pareto plotting:
  - *Improve Pareto point distribution for weighted objective sum*
  - *Simple changes to simplify GUI*
- 3-D metamodel plot enhancements
  - *Activate Post-Processor on point selection*
  - *Add value list display on point selection (similar to 2D)*
  - *Improve interface (e.g. selection options)*

## → Next Steps – Version 4.0

- Redesign of Viewer
  - *2-Dimensional Metamodeler*
  - *Multi-Plot capability*
- Combinatorial Optimization
  - *Material type (integer) optimization*
  - *Improve of Multiobjective Optimization*
- Redesign Trade-off interface
  - *Improve interactivity to generate Pareto curve*
- Simplification of Min.-Max. optimization
  - *Option similar to MeanSqErr*
  - *Generates internal constraints*

## → Next Steps – Version 4.0

- LS-OPT report
  - *Summary report of optimization and stochastic results*
  - *suitable format to be chosen (GUI)*
- More direct Methods
  - *Gradient based*
  - *Genetic/Evolutionary Algorithms*



**Thanks for your attention!**