Robust Design Optimization of a Centrifugal Compressor concerning Fluid-Structure Interaction and Manufacturing Tolerances

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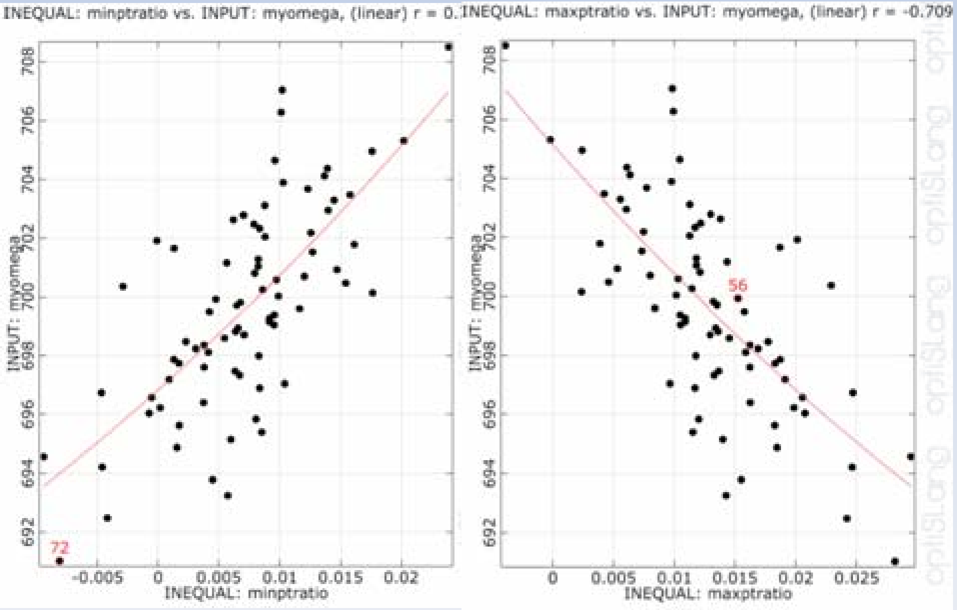
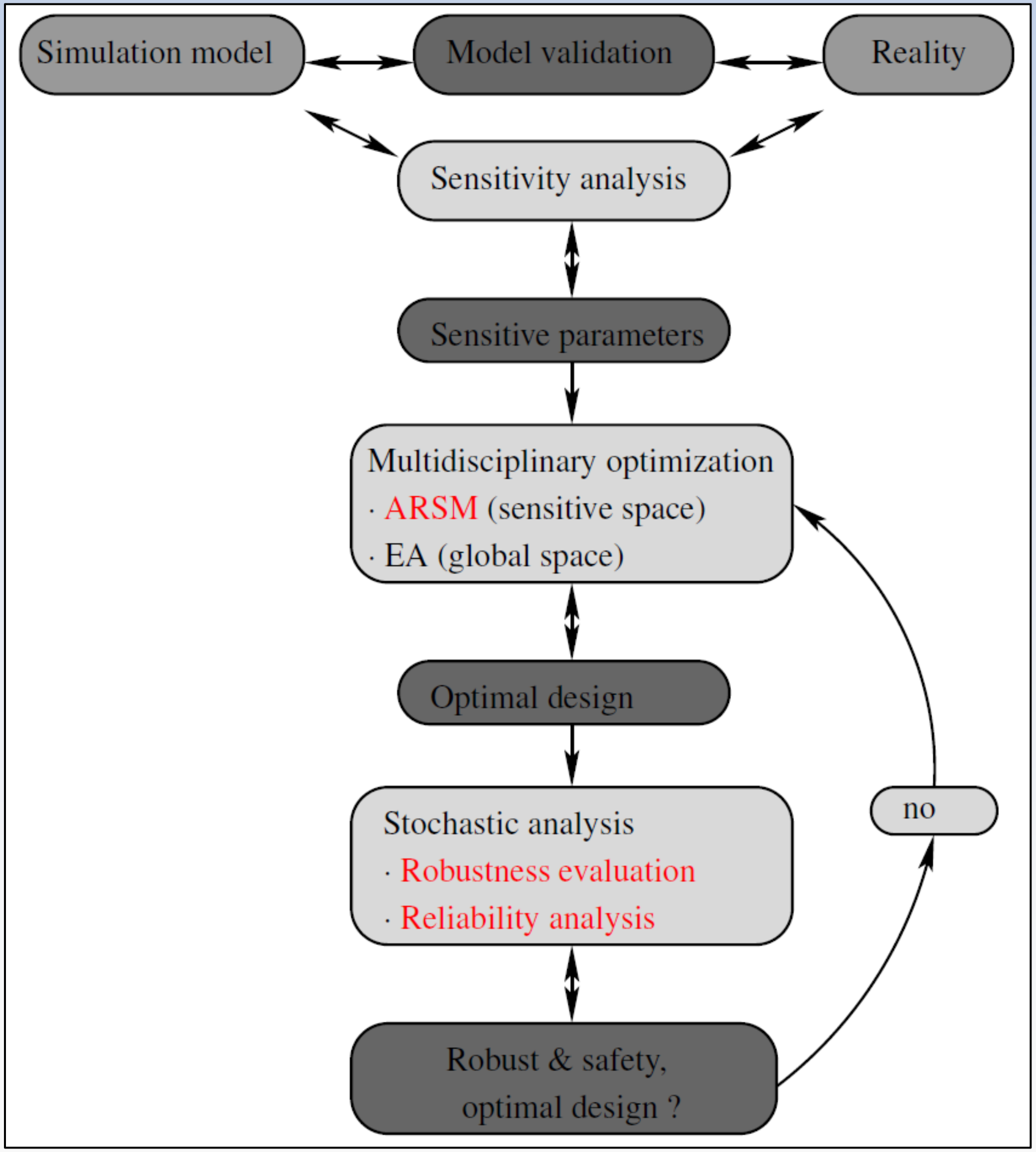
Conclusion Robustness Analysis

- Non robust behavior with respect to
  - **Efficiency**
  - **Total pressure**
- But acceptable failure probability level for structural risk
  - Estimation of a Six Sigma Design
- Efficiency: **myeta**
  - RVHubBeta1 as largest as possible
  - RVShdBeta1 as largest as possible
  - RImpeller as smallest as possible
- Total pressure: **ptratio**
  - myomega as largest as possible
  - RImpeller as largest as possible
  - ptratio mean -> 1.355



Successive Robust Design Optimization



- iterative decoupled loop approach
- in combination with identification of the most significant random and design variables using the multivariate statistic
- first step the robustness evaluation can be used to prove the predictive capability of the simulation model and to
- identify the most important parameters to solve reliability analysis, efficiently
- it is neccessary to evaluate robustness and safety of the design

Design Optimization II

Robustness Evaluation II

Robust Design Optimization

Reliability Analysis

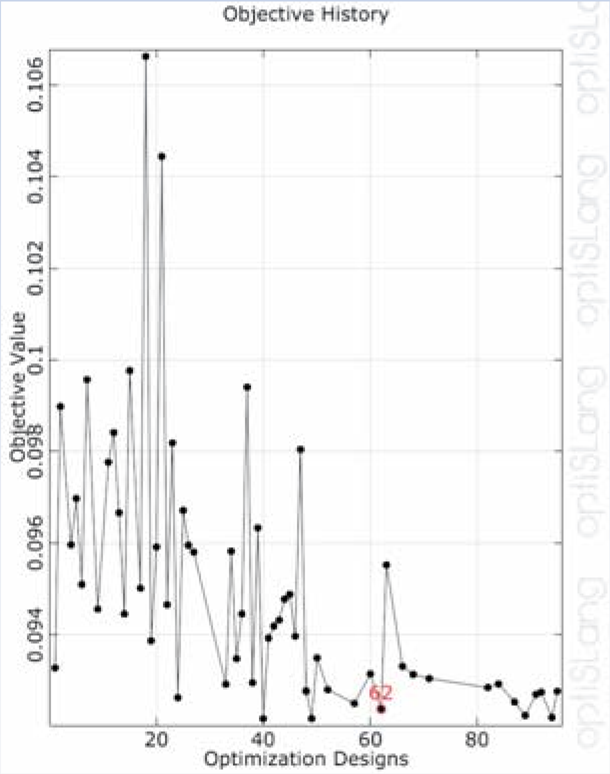
Design Optimization II

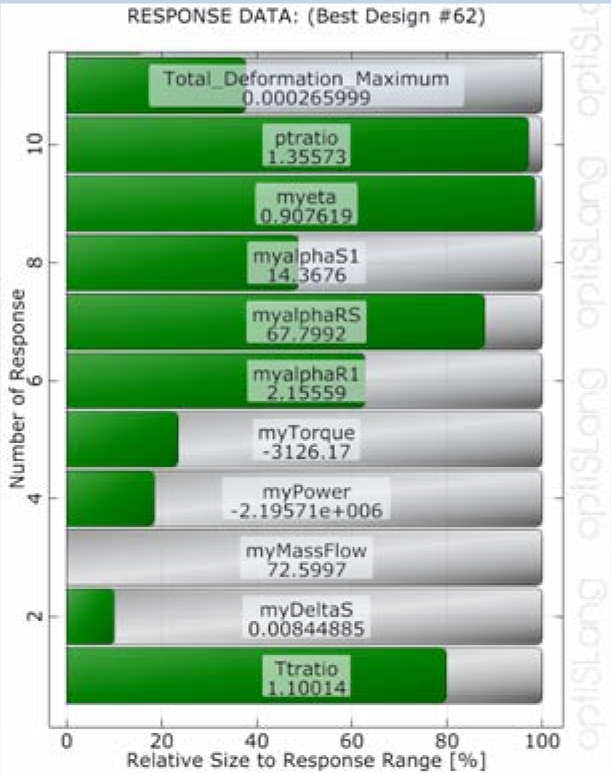
Opti | Robust | Output | Strings | Constraints | Objectives

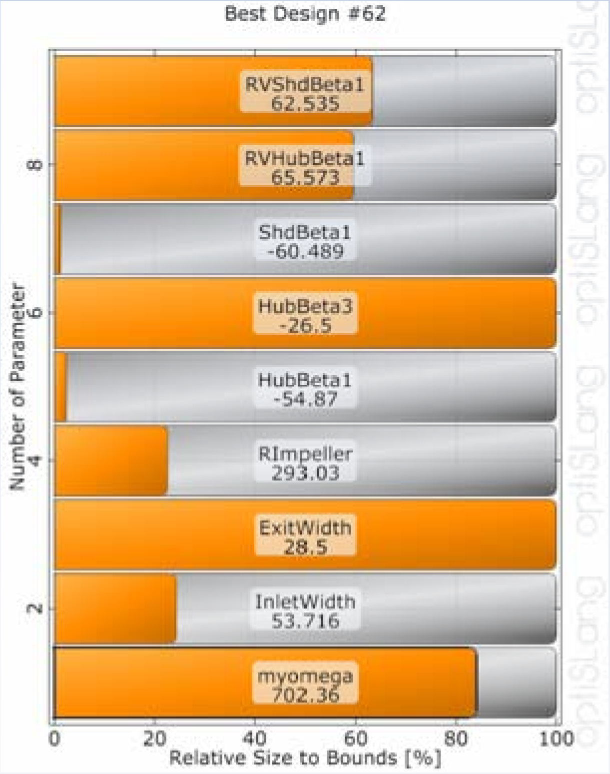
#	Name	Value	Ref.Value	Lower Bound	Upper Bound	Type	Format	Active	Const...
1	myomega	699.76	699.76	699.0	703.0	continuous	%20.14f	[x]	[ ]
2	InletWidth	53	53.6136610657...	52.5	57.5	continuous	%20.14f	[x]	[ ]
3	ExitWidth	26	27.8049298398...	26.5	28.5	continuous	%20.14f	[x]	[ ]
4	RImpeller	305	292.556879245...	291	300	continuous	%20.14f	[x]	[ ]
5	HubBeta1	-48	-52.5	-55	-49.5	continuous	%20.14f	[x]	[ ]
6	HubBeta3	-25	-27.017132519...	-28	-26.5	continuous	%20.14f	[x]	[ ]
7	ShdBeta1	-55	-60.267623161...	-60.5	-59.5	continuous	%20.14f	[x]	[ ]
8	RVHubThk1	45	45.0	35	66.0	continuous	%20.14f	[x]	[ ]
9	RVHubBeta1	60	66.0	62.0	68	continuous	%20.14f	[x]	[ ]
10	RVShdBeta1	60	62.8548646835...	60.0	64.0	continuous	%20.14f	[x]	[ ]
11	RVShdThk1	45	45.0	35.0	55.0	continuous	%20.14f	[x]	[ ]
12	HubBeta2	-25	-25.0	-27.5	-22.5	continuous	%20.14f	[ ]	[x]
13	ShdBeta2	-45	-45.0	-49.5	-40.5	continuous	%20.14f	[ ]	[x]
14	ShdBeta3	-30	-30.0	-33.0	-27.0	continuous	%20.14f	[ ]	[x]
15	HubThk1	1	1.0	0.8	1.2	continuous	%20.14f	[ ]	[x]
16	HubThk2	6	5.91963645103...	5.0	7.0	continuous	%20.14f	[ ]	[x]
17	ShdThk1	1	1.03011230706...	0.8	1.2	continuous	%20.14f	[ ]	[x]
18	ShdThk2	6	6.0	5.0	7.0	continuous	%20.14f	[ ]	[x]
19	ImpellerBlades	20	20	18.0	24.0	continuous	%20.14f	[ ]	[x]
20	RVBlades	24	24	21.6	28.7999999999...	continuous	%20.14f	[ ]	[x]

Cancel | OK

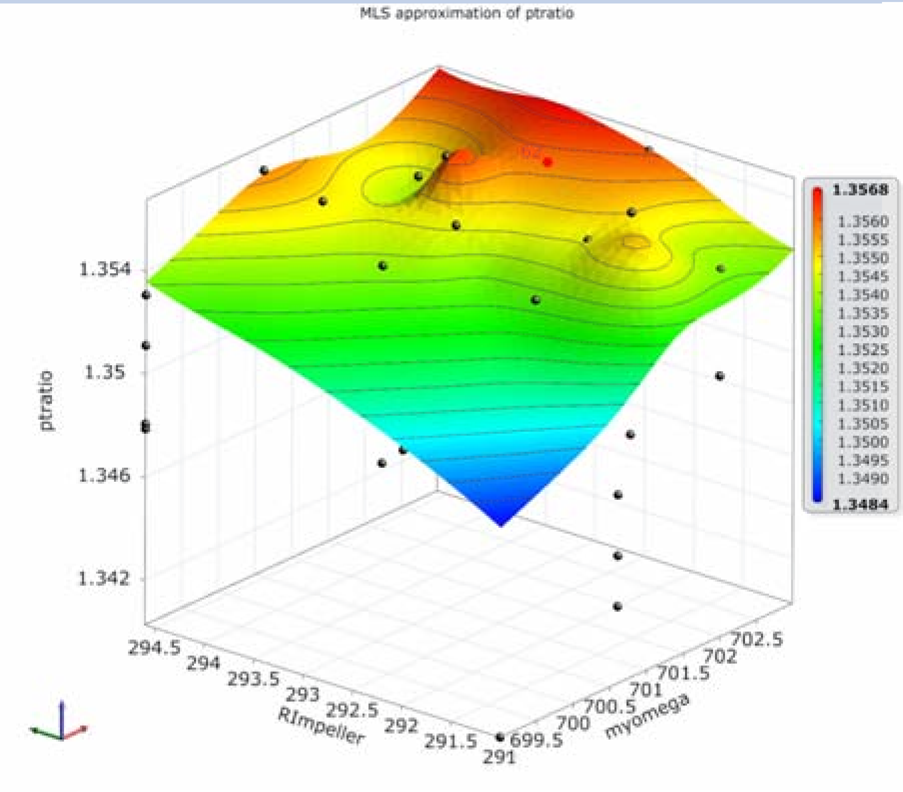
Design Optimization II: ARSM

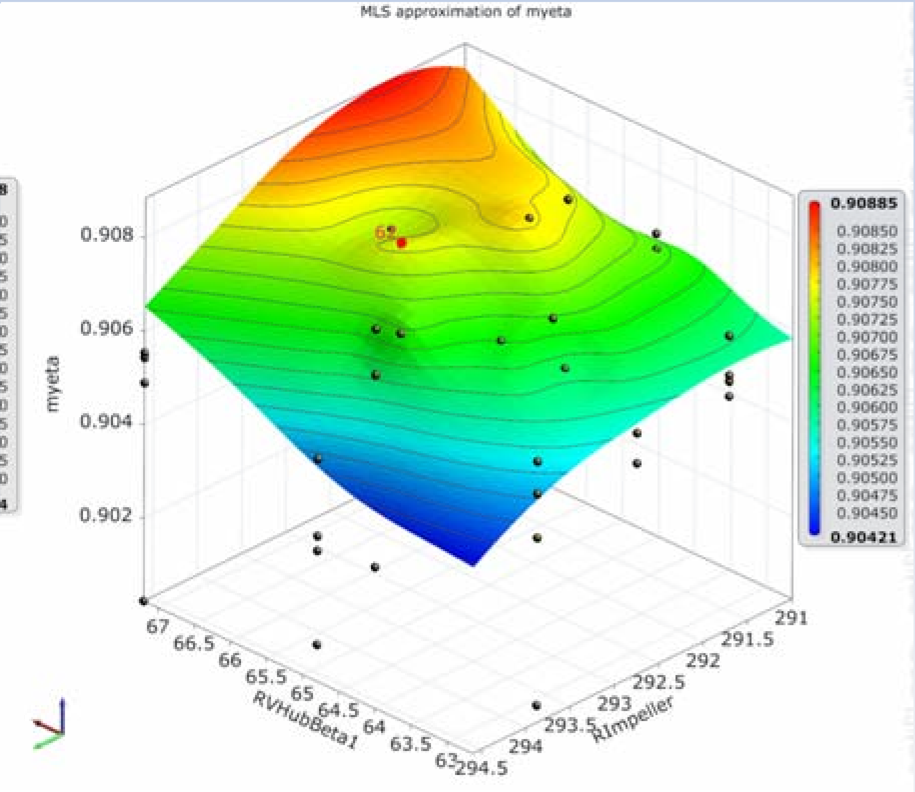






Design Optimization II: ARSM





	Initial	SA	ARSM I	EA I	ARSM II
Total Pressure Ratio	1.3456	1.3497	1.3479	1.3485	1.356
Efficiency [%]	86.72	89.15	90.62	90.67	90.76
#Designs	-	100	105	84	62

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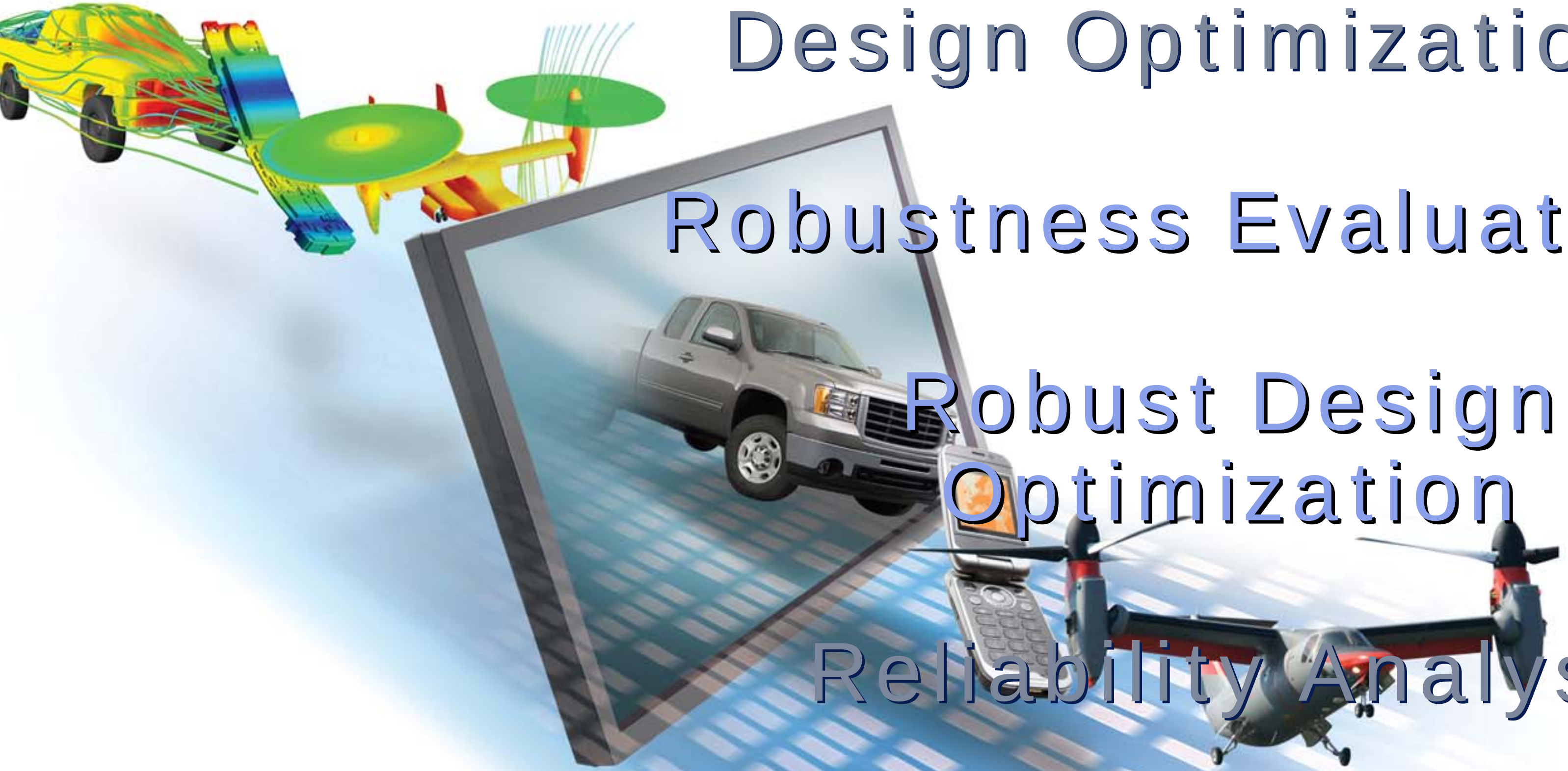


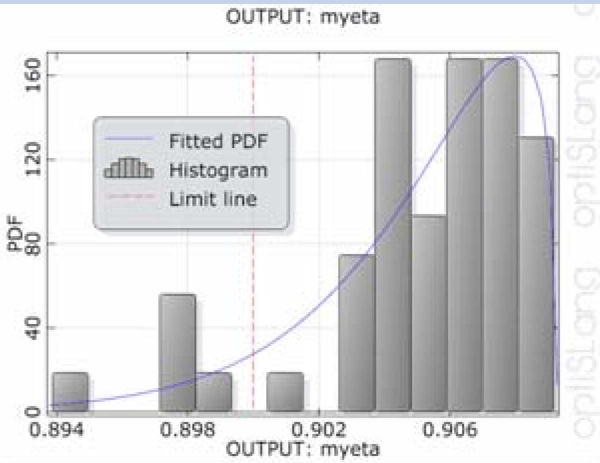
Design Optimization II

Robustness Evaluation II

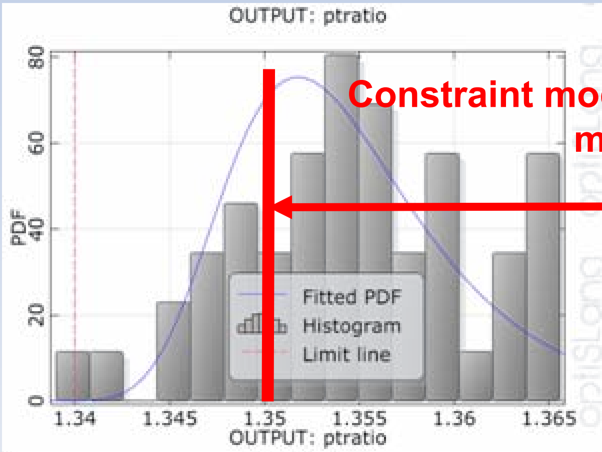
Robust Design Optimization

Reliability Analysis

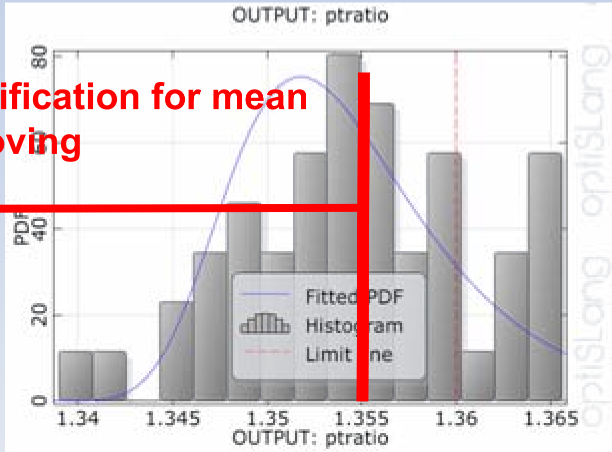
Robust evaluation II: LHS



Statistic data			
Min:	0.8939	Max:	0.9092
Mean:	0.9051	Sigma:	0.00329
CV:	0.003635		
Skewness:	-1.487	Kurtosis:	4.997
Fitted PDF: Extreme Typ III (Min) Weibull			
Mean:	0.9051	Sigma:	0.00329
Upper cut:	0.9092		
Limit x = 0.9			
P_rel =	0.102041	P_fit =	0.0808577



Statistic data			
Min:	1.339	Max:	1.366
Mean:	1.355	Sigma:	0.006258
CV:	0.00462		
Skewness:	-0.1853	Kurtosis:	2.623
Fitted PDF: Fisher-Tippett			
Mean:	1.355	Sigma:	0.006258
Limit x = 1.34			
P_rel =	0.0204082	P_fit =	1.4437e-005



Statistic data			
Min:	1.339	Max:	1.366
Mean:	1.355	Sigma:	0.006258
CV:	0.00462		
Skewness:	-0.1853	Kurtosis:	2.623
Fitted PDF: Fisher-Tippett			
Mean:	1.355	Sigma:	0.006258
Limit x = 1.36			
P_rel =	0.795918	P_fit =	0.831174

Constraint modification for mean moving

Tolerance limit η<90%
~8% outside

Tolerance limit
Π_T>1.36
~17% outside

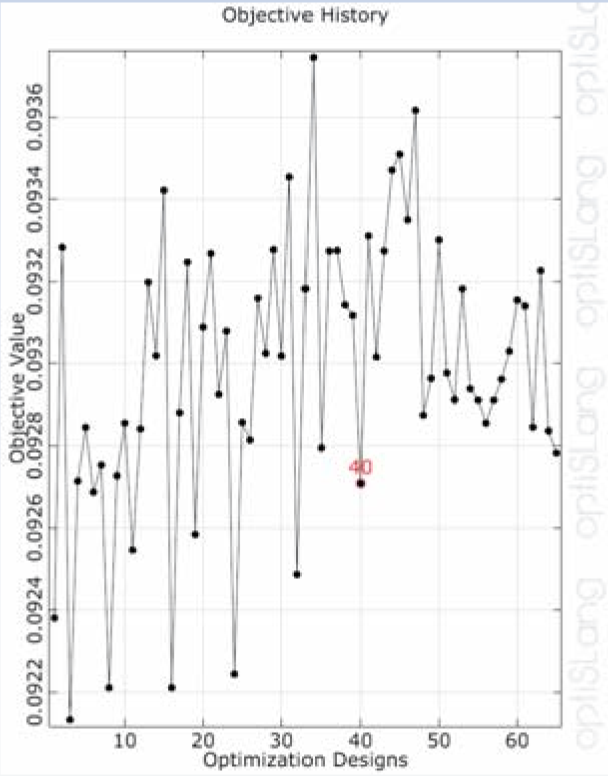
Design Optimization III

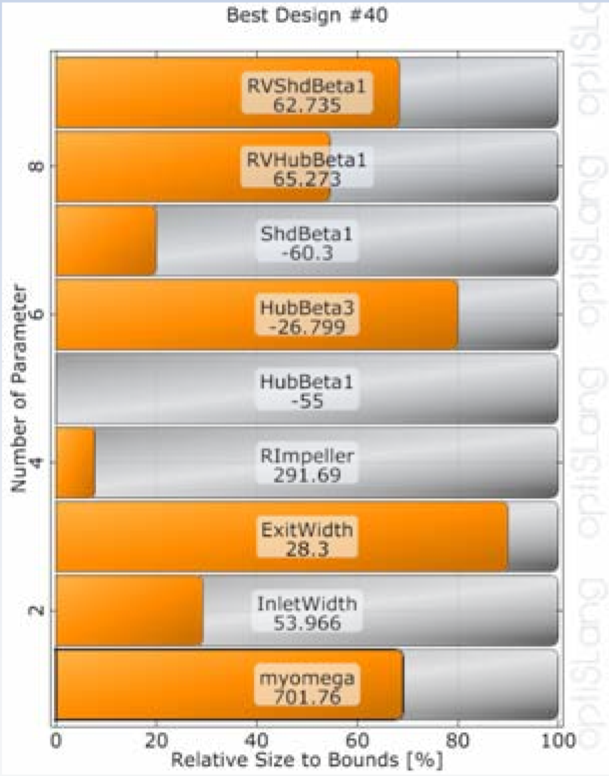
Robustness Evaluation III

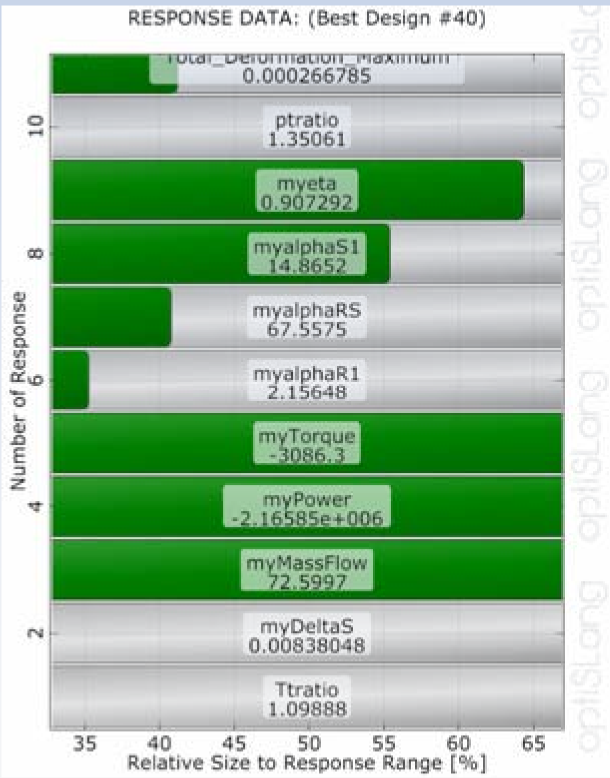
Robust Design Optimization

Reliability Analysis

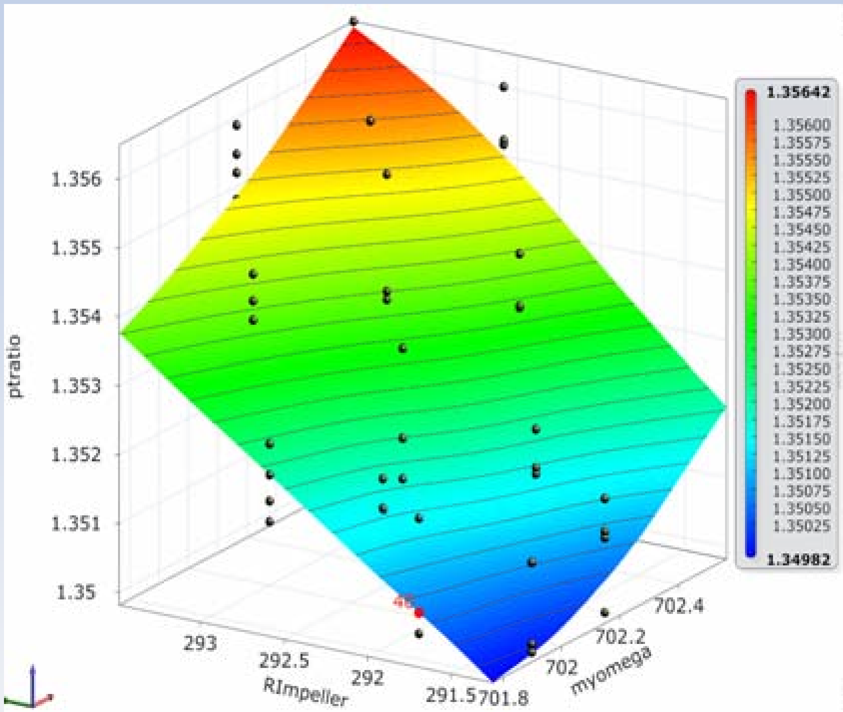
Design Optimization III: ARSM

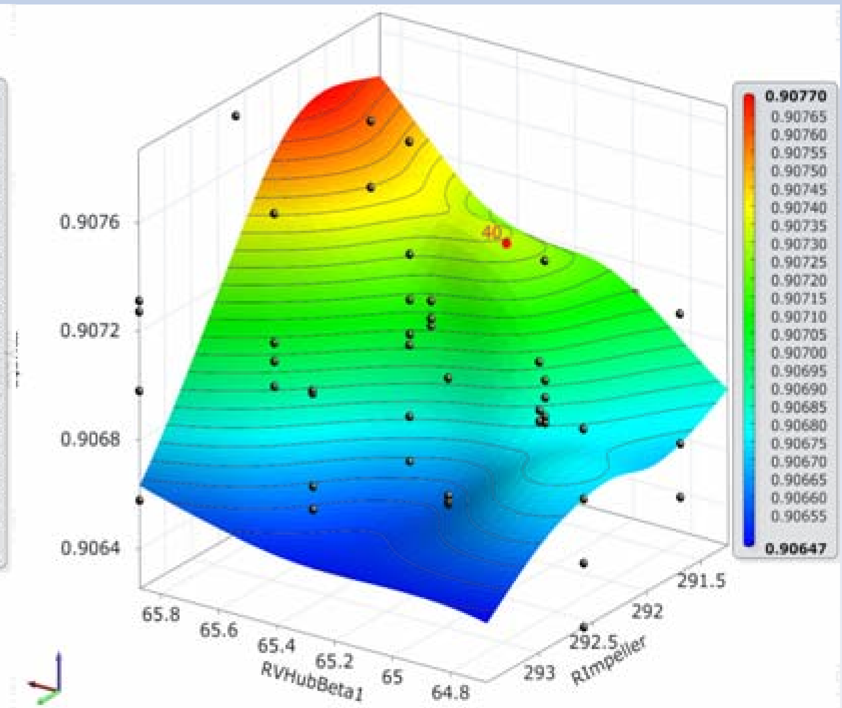






Design Optimization III: ARSM





	Initial	SA	ARSM I	EA I	ARSM II	ARSM III
Total Pressure Ratio	1.3456	1.3497	1.3479	1.3485	1.356	1.351
Efficiency [%]	86.72	89.15	90.62	90.67	90.76	90.73
#Designs	-	100	105	84	62	40

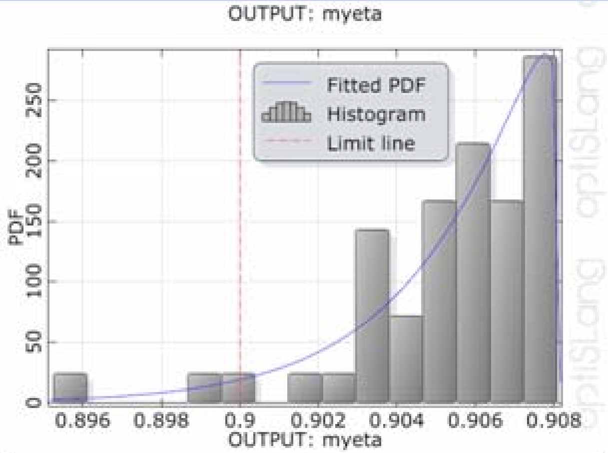
Design Optimization III

Robustness Evaluation III

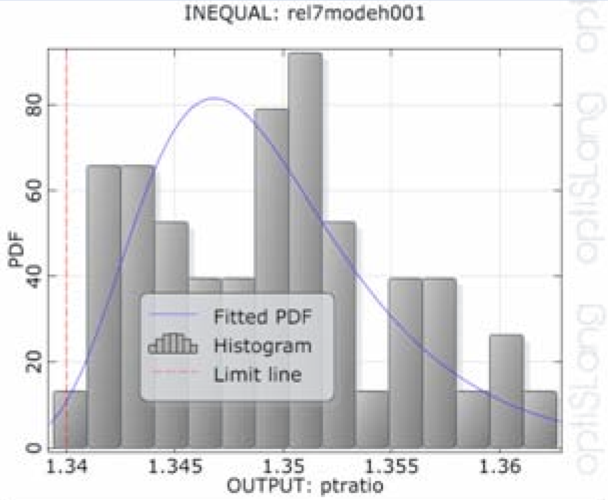
Robust Design Optimization

Reliability Analysis

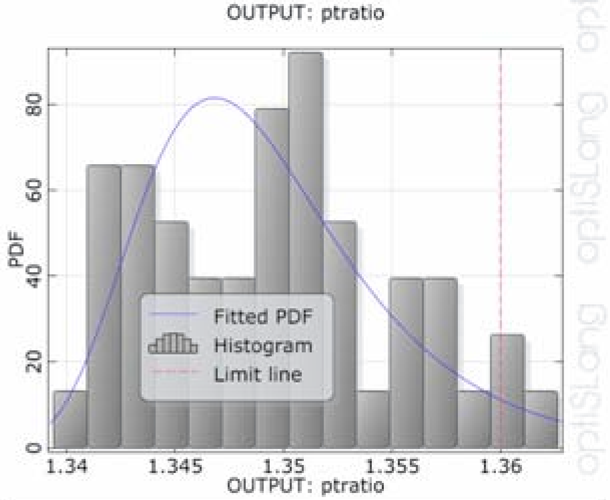
Robust evaluation III: LHS



Statistic data			
Min:	0.8953	Max:	0.9081
Mean:	0.9053	Sigma:	0.002554
CV:	0.002821		
Skewness:	-1.868	Kurtosis:	7.173
Fitted PDF: Extreme Typ III (Min) Weibull			
Mean:	0.9053	Sigma:	0.002554
Upper cut:	0.9081		
Limit x = 0.9			
P_rel =	0.0612245	P_fit =	0.0453854



Statistic data			
Min:	1.339	Max:	1.363
Mean:	1.349	Sigma:	0.005782
CV:	0.004285		
Skewness:	0.3347	Kurtosis:	2.38
Fitted PDF: Fisher-Tippett			
Mean:	1.349	Sigma:	0.005782
Limit x = 1.34			
P_rel =	0.0204082	P_fit =	0.01082



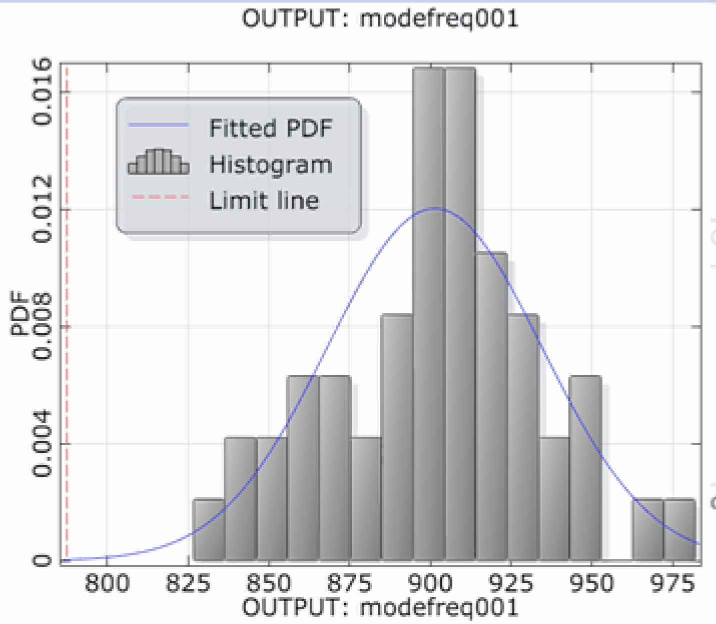
Statistic data			
Min:	1.339	Max:	1.363
Mean:	1.349	Sigma:	0.005782
CV:	0.004285		
Skewness:	0.3347	Kurtosis:	2.38
Fitted PDF: Fisher-Tippett			
Mean:	1.349	Sigma:	0.005782
Limit x = 1.36			
P_rel =	0.938776	P_fit =	0.947814

Tolerance limit η<90%
~4.5% outside

Robust Design

Tolerance limit
$1.4<\Pi_T<1.36$
~6% outside

Robust evaluation III: Eigen Frequency Mode 1 Harmonic Index 0

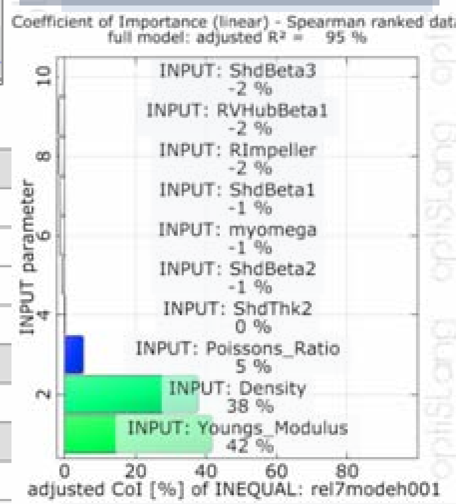


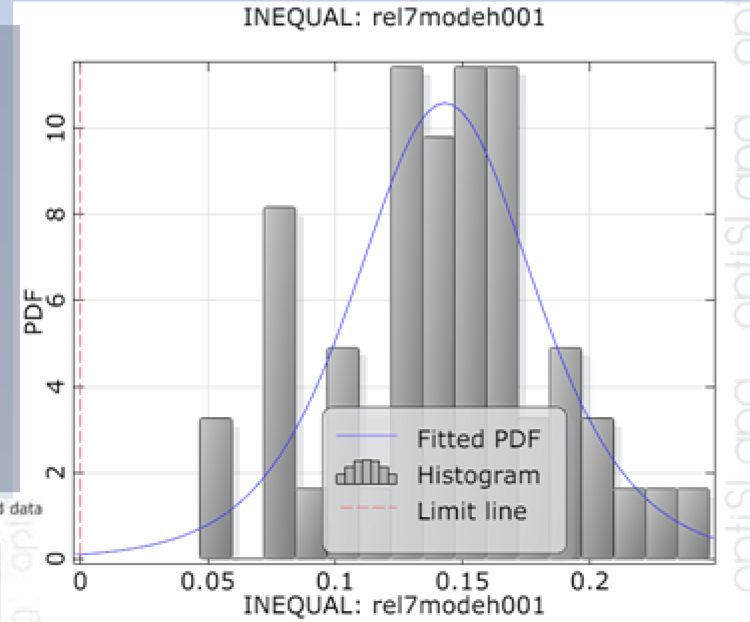
Statistic data			
Min:	826.6	Max:	982
Mean:	901.3	Sigma:	33.18
CV:	0.03682		
Skewness:	-0.04593	Kurtosis:	2.862
Fitted PDF: Normal			
Mean:	901.3	Sigma:	33.18
Limit x = 787.4			
P_rel =	0	P_fit =	0.000299089

Tolerance limit: Resonance point ~ 120/240 Hz

μ_{RP001} ~ 937 Hz

σ_{RP001} ~ 34 Hz





Statistic data			
Min:	0.04693	Max:	0.2468
Mean:	0.1431	Sigma:	0.04281
CV:	0.2991		
Skewness:	-0.1285	Kurtosis:	2.936
Fitted PDF: Logistic			
Mean:	0.1431	Sigma:	0.04281
Limit x = 0			
P_rel =	0	P_fit =	0.0023215

$P(\mathcal{F}) \leq 3.4 \cdot 10^{-6}; (\beta = \sigma_L \geq 4.5)$

$P(\mathcal{F}) \approx \Phi(-\beta) \approx \Phi(-0.143 + 0.01/0.0428) = \Phi(-3.11) = 9.4 \cdot 10^{-4}$

Safety Design?

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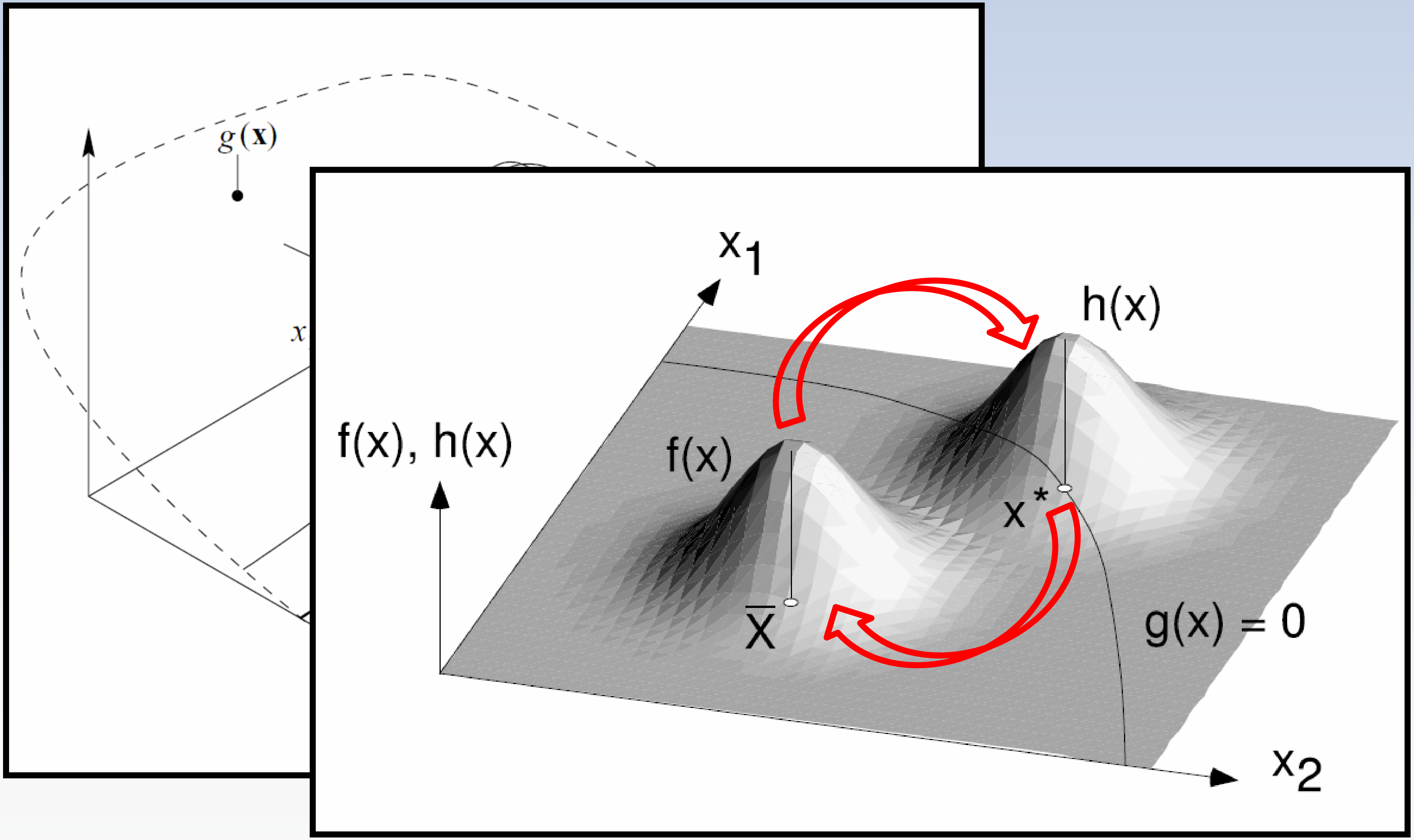
Design Optimization

Robustness Evaluation

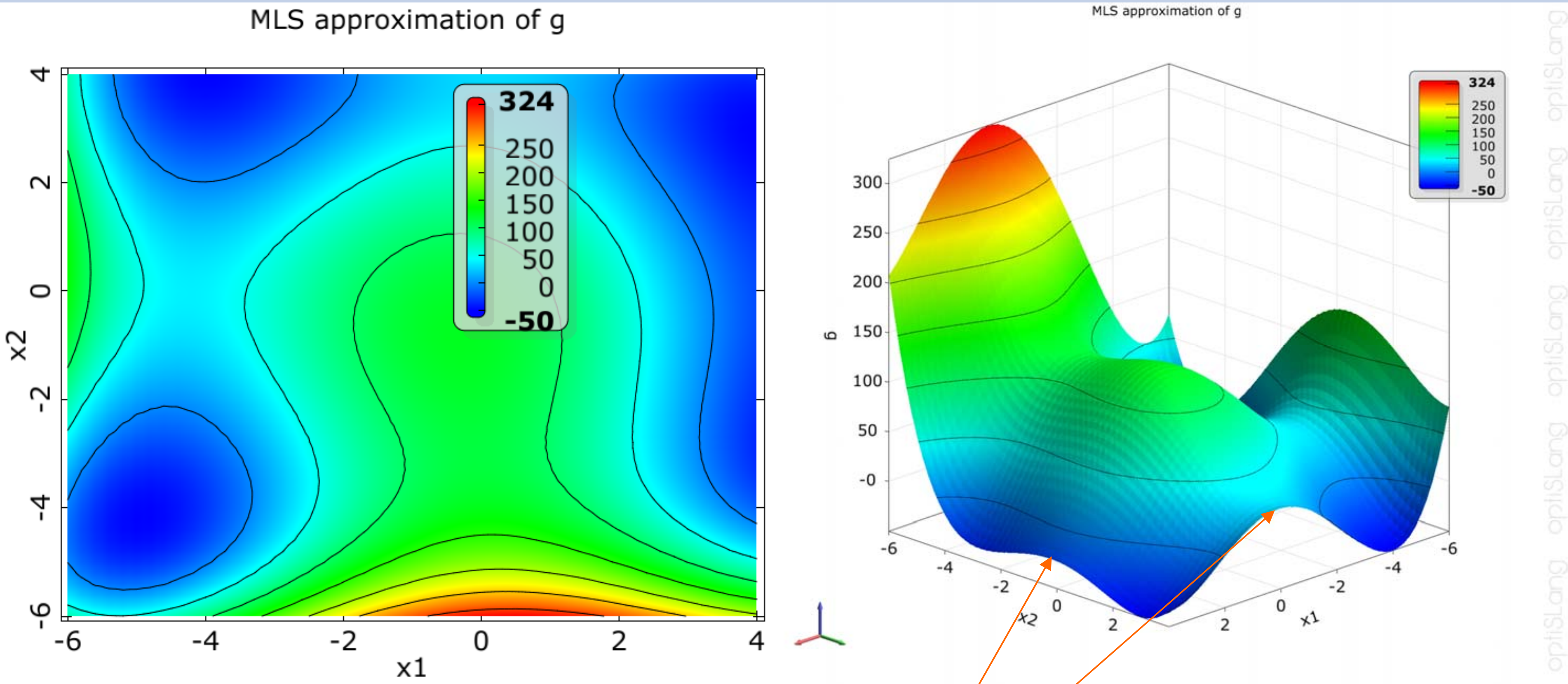
Robust Design Optimization

Reliability Analysis

Reliability Analysis

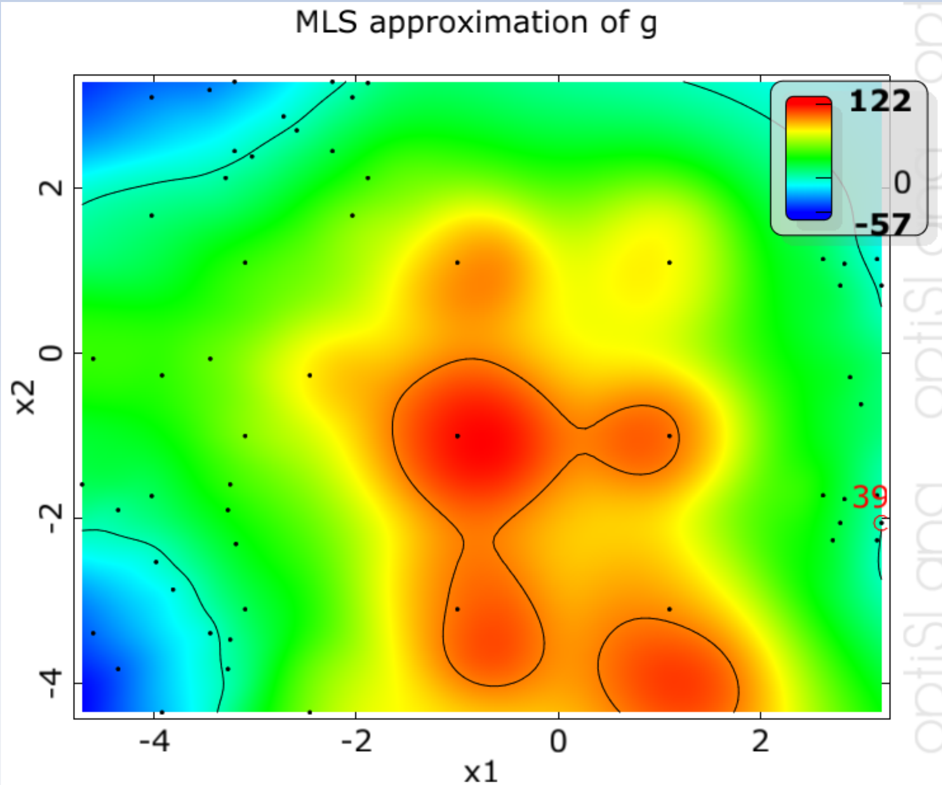


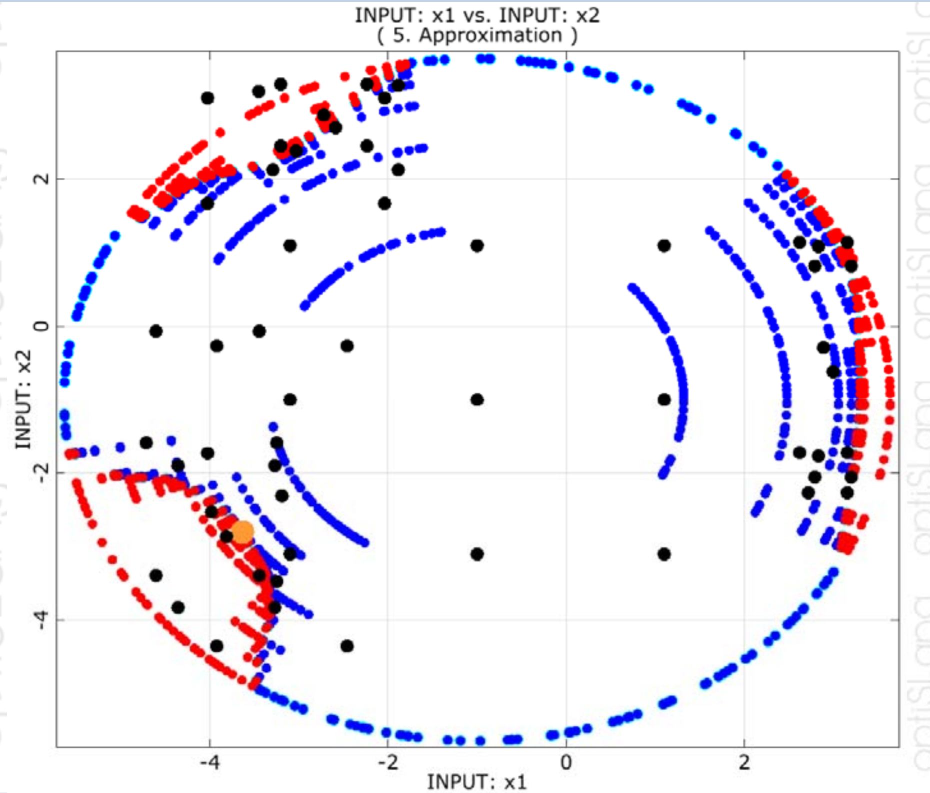
Reliability Analysis



- Himmelblau function
- Nonlinear two dimensional state function g(x1,x2)
- Nonlinear limit state function g(x1,x2)=0
- Three separated domains with high failure probability density

Reliability Analysis

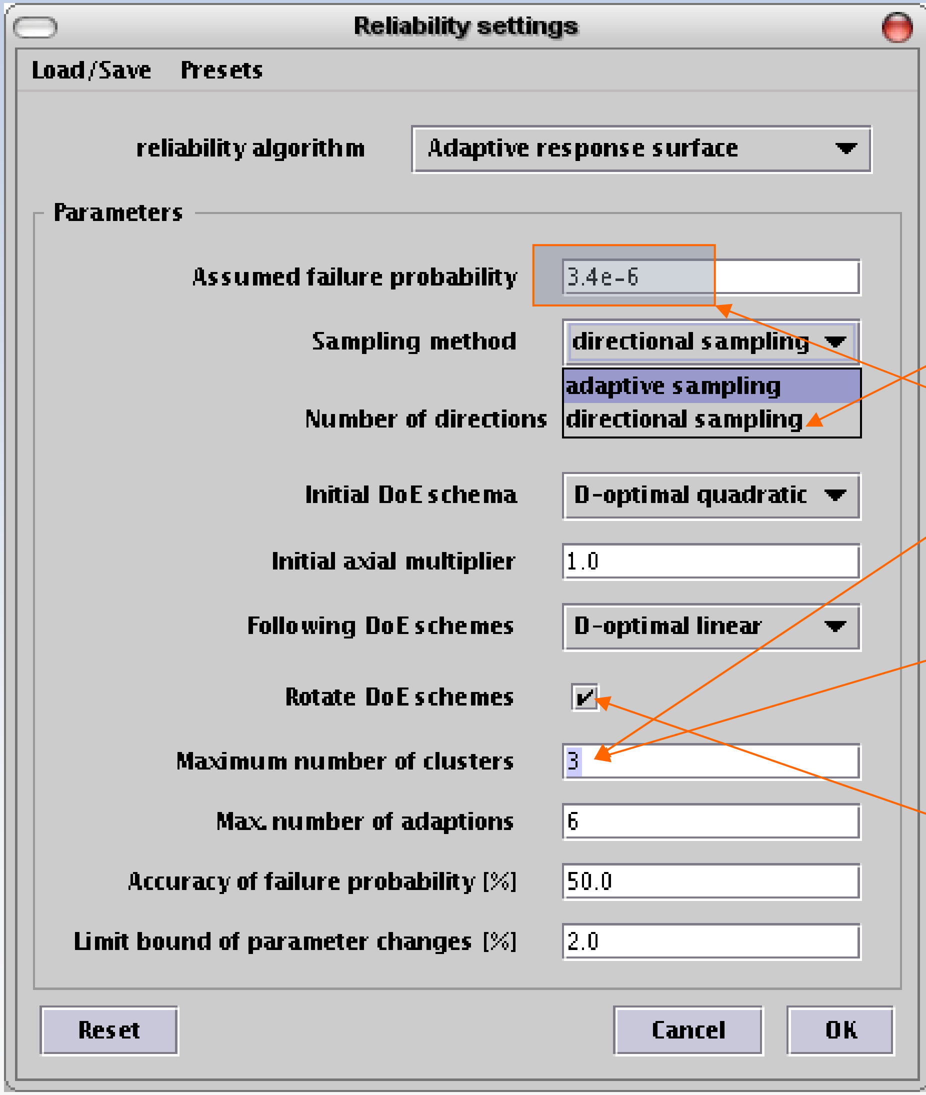




- Adaptive response surface method
- Directional sampling on MLS
- Design evaluations: 58
- PF = 1.67E-06 (1.99E-06)

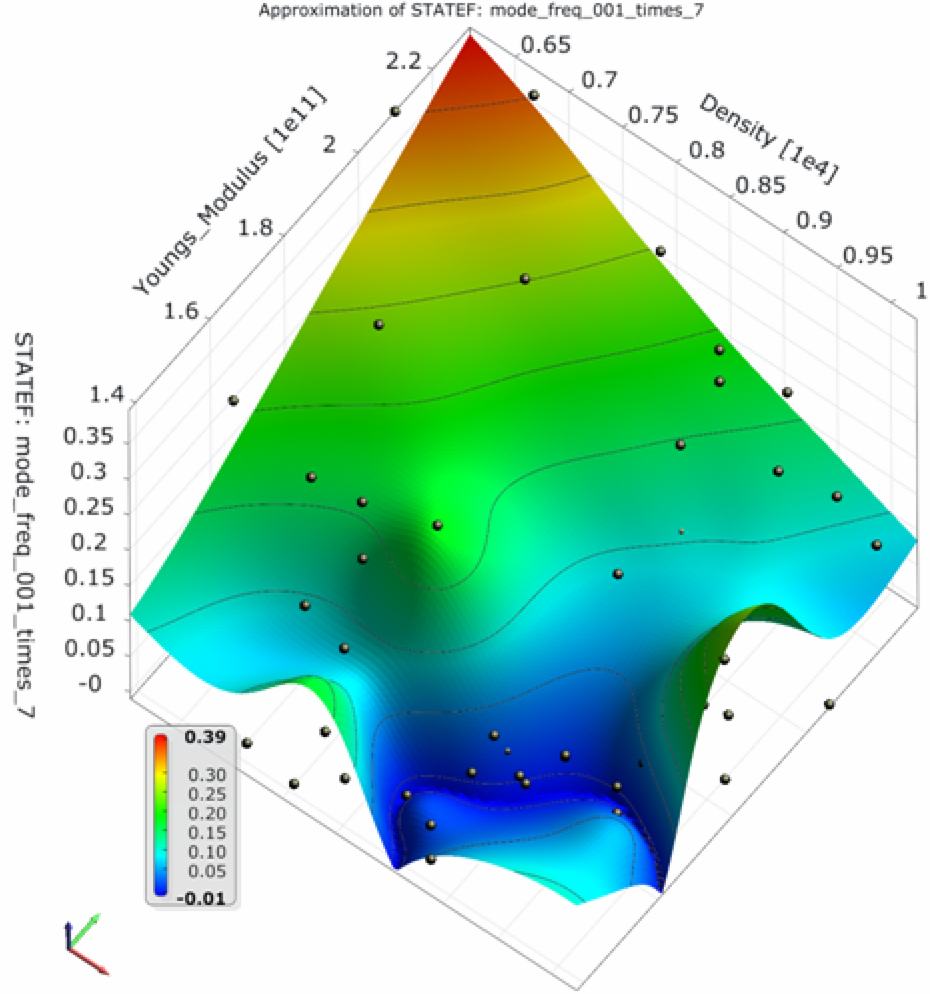
- Sigma level independent
- n ≤ 20
- Multiple adaptive DOE
- Supports multi-domain limit states

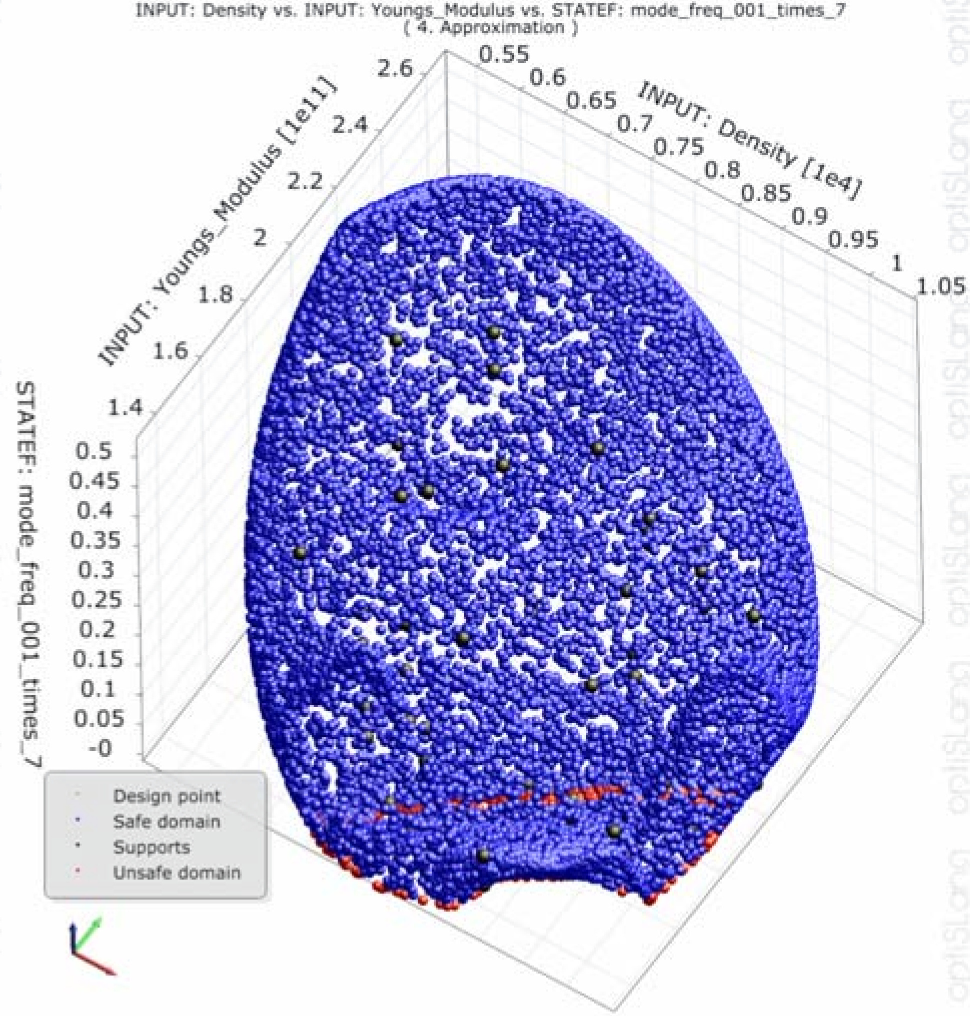
Adaptive response surface approximation



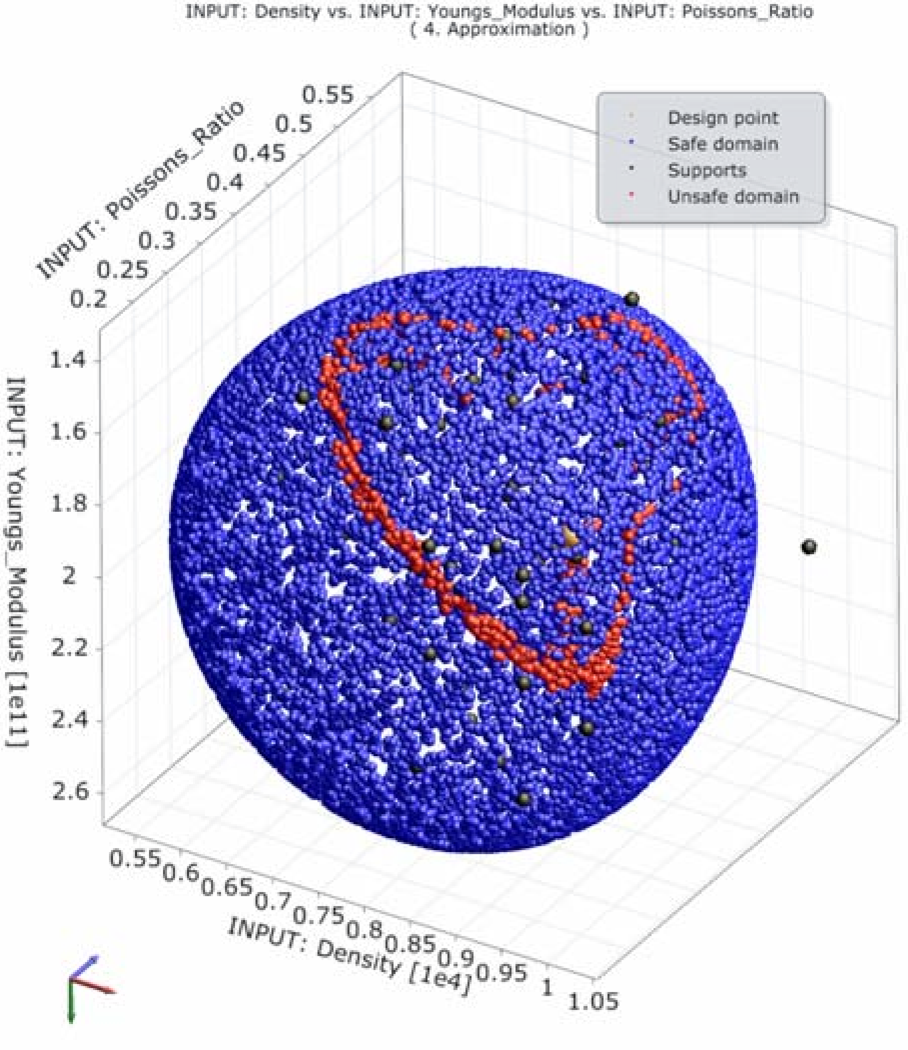
- Sampling methods on the MLS approximation:
  - Adaptive Sampling
  - Directional Sampling
    - supports more than two failure domains
    - and sigma level independent
- Cluster analysis to detect number of failure domains with high failure probability
- Rotatable adaptive designs of experiments to improve the approximation accuracy

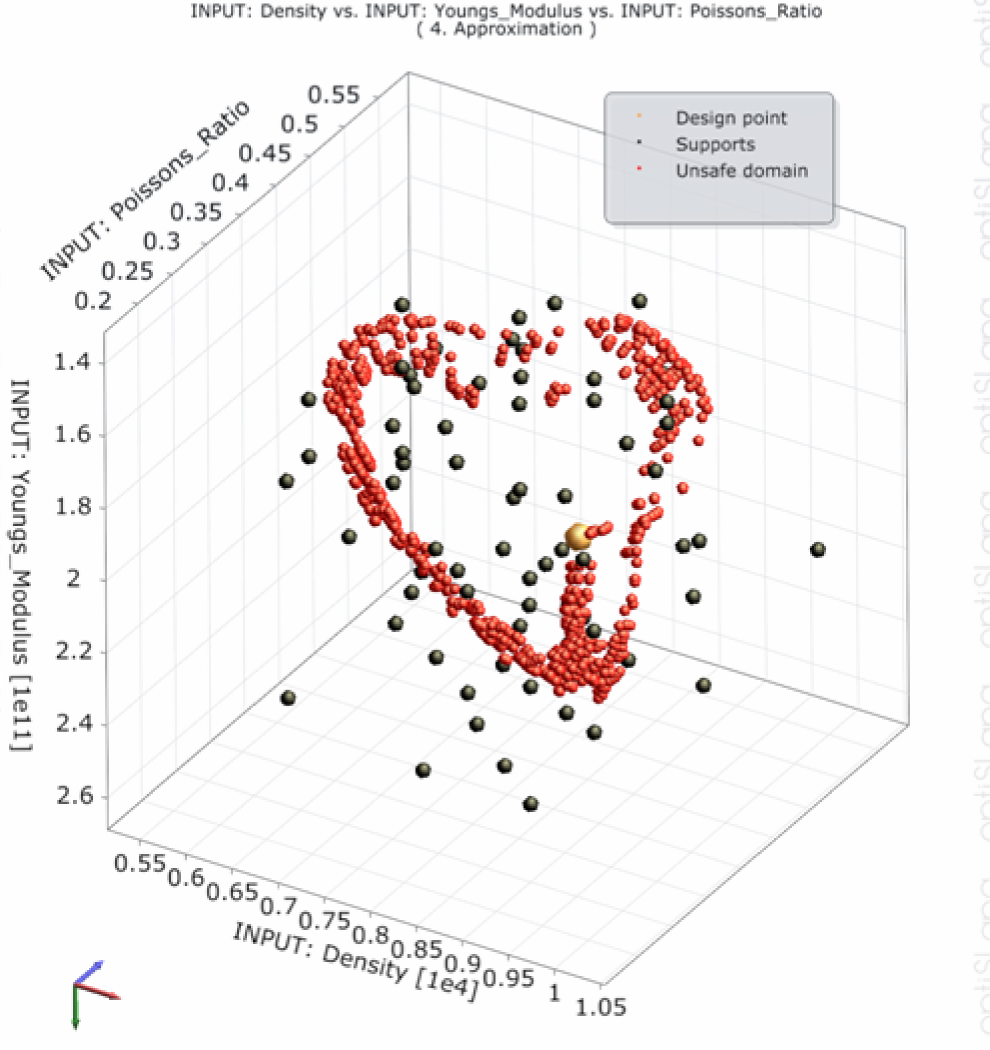
Reliability Analysis



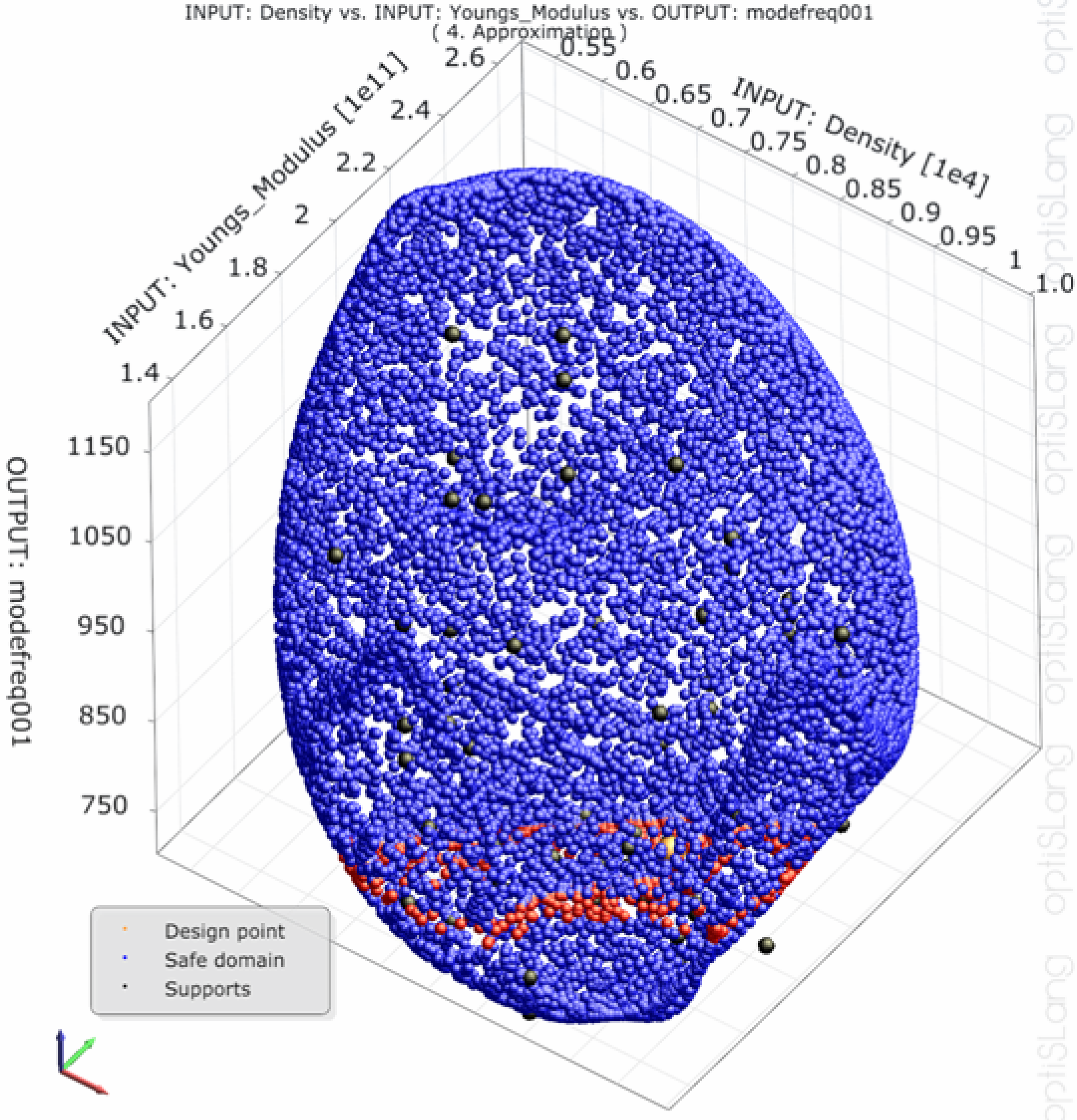


Reliability Analysis





Reliability Analysis



Method : Directional Sampling on Adaptive Response Surfaces (ARSM-DS)

Selected data : 4. Approximation

Number of designs : 68 (4 failed)

Complete directions : 10000 / 10000

Number of samples :
Total : 13640
Safe domain : 11891
Unsafe domain : 1749
Failure strings : 0
Unsuccessful : 0

Probability of failure : 2.75e-007 (2.75e-007)
Standard deviation error : 6.667e-008 (6.667e-008)

Most probable failure point:

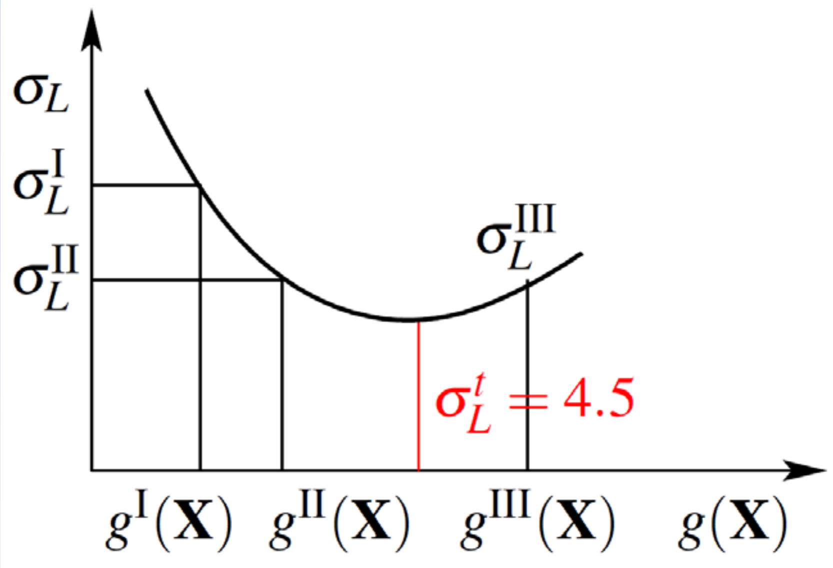
Density :9279.86887124
Youngs_Modulus :177034428177
Poissons_Ratio :0.285958415968

Distance median - design point (beta) : 4.328

Probability of failure (FORM): 7.526e-006

- n = 3 random parameters
- N = 68 design evaluations
- $P(\mathcal{F}) \approx 3 \cdot 10^{-7} < 3.4 \cdot 10^{-6}$
- Six Sigma Design

Summary



- Parametric Workflow management
- Automatic and embedded solution
- Parallel and distributed solver runs
- Process integration within optiSLang
- Efficient Robust Design Optimization with
- Quadratic convergence rate and
- 18 design parameters and
- 26 random geometry parameters,
- including the manufactoring tolerances based random field modelling
- Optimized robust design:
  5% improvement of the efficiency (η<90%, failure rate ~4.5%)
  Tolerance limit (1.4<Π_T<1.36, failure rate ~6%)
- Optimized Six Sigma design $P(\mathcal{F}) \approx 3 \cdot 10^{-7}$
- N = 100 + 105 + 84 + 100 + 62 + 50 + 40 + 50 + 68 = 659 design evaluations
  (SA)(EA)(ARSM)(RE)(ARSM)(RE)(ARSM)(RE)(RA)
- Calculation time: 10 days (8 CPUs)