Robust Design Optimization of a Centrifugal Compressor Part I

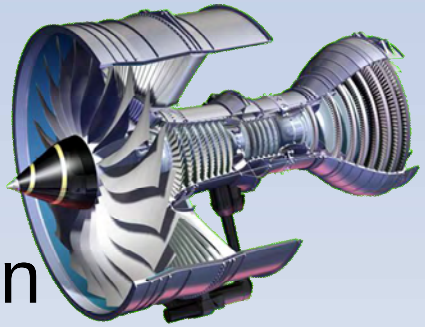
optiSLang
optimizing structural language

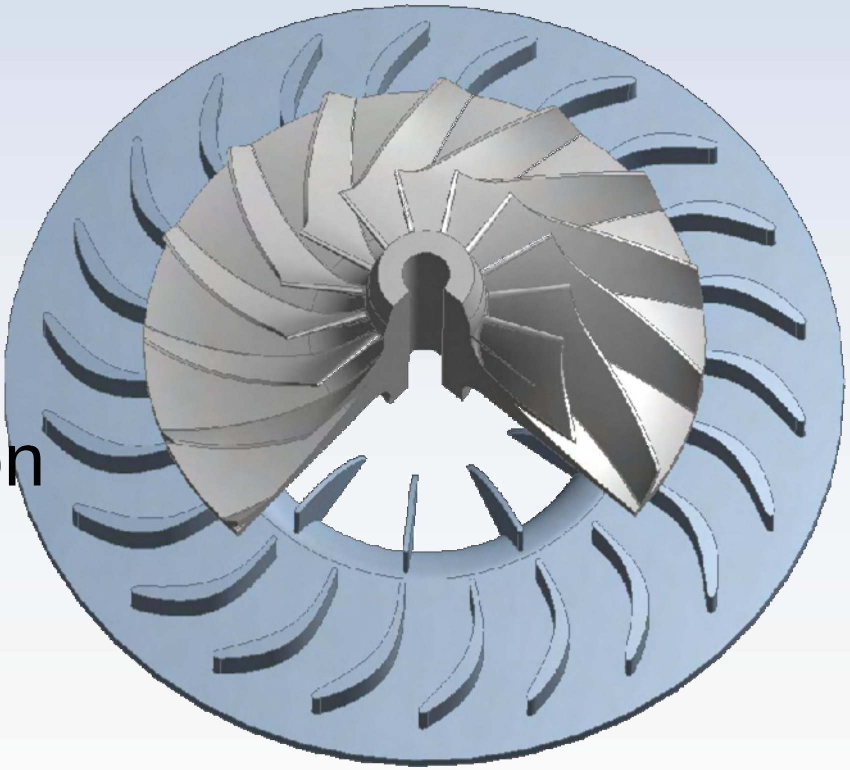
Dirk Roos
DYNARDO GmbH
dirk.roos@dynardo.de

Johannes Einzinger
ANSYS Continental Europe
johannes.einzinger@ansys.com

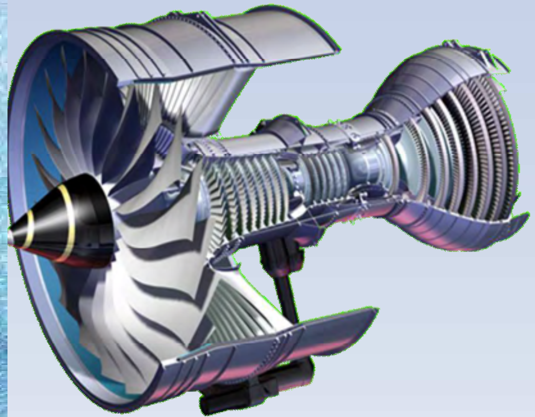
Outline

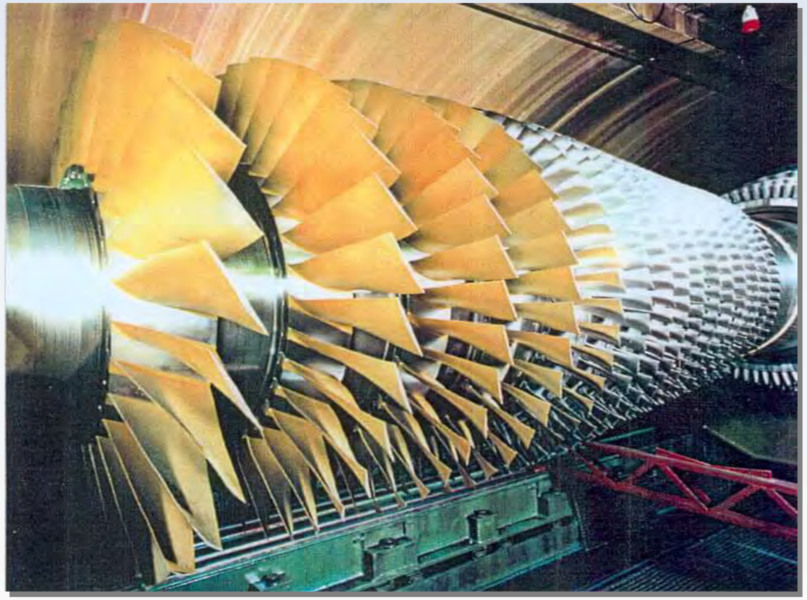
- Parameterization Geometry
- Parameterization CFD Simulation
- Parameterization Mechanical Simulation
- Parametric Process
- Sensitivity Analysis
- Design Optimization
- Robustness Evaluation
- Robust Design Optimization





Motivation





Power Plant	**1000 MW**
Efficiency	**50 %**
Increase of 1%	**+20 MW**
=Electricity for	**120 000 Inhabitants**

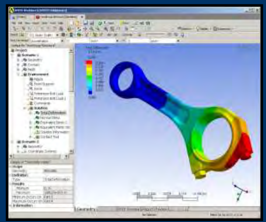
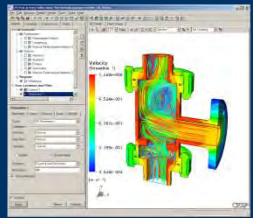
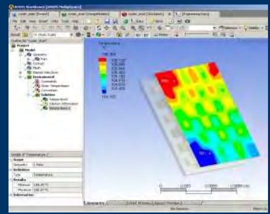
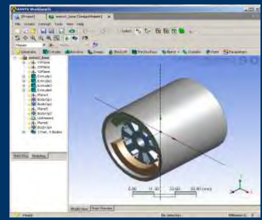
Workbench & optiSLang

CAD / PDM

CATIA · SolidWorks · UGS The PLM Company · PTC · autodesk

ANSYS Workbench

Structural Mechanics - Fluid Dynamics - Heat Transfer - Electromagnetic

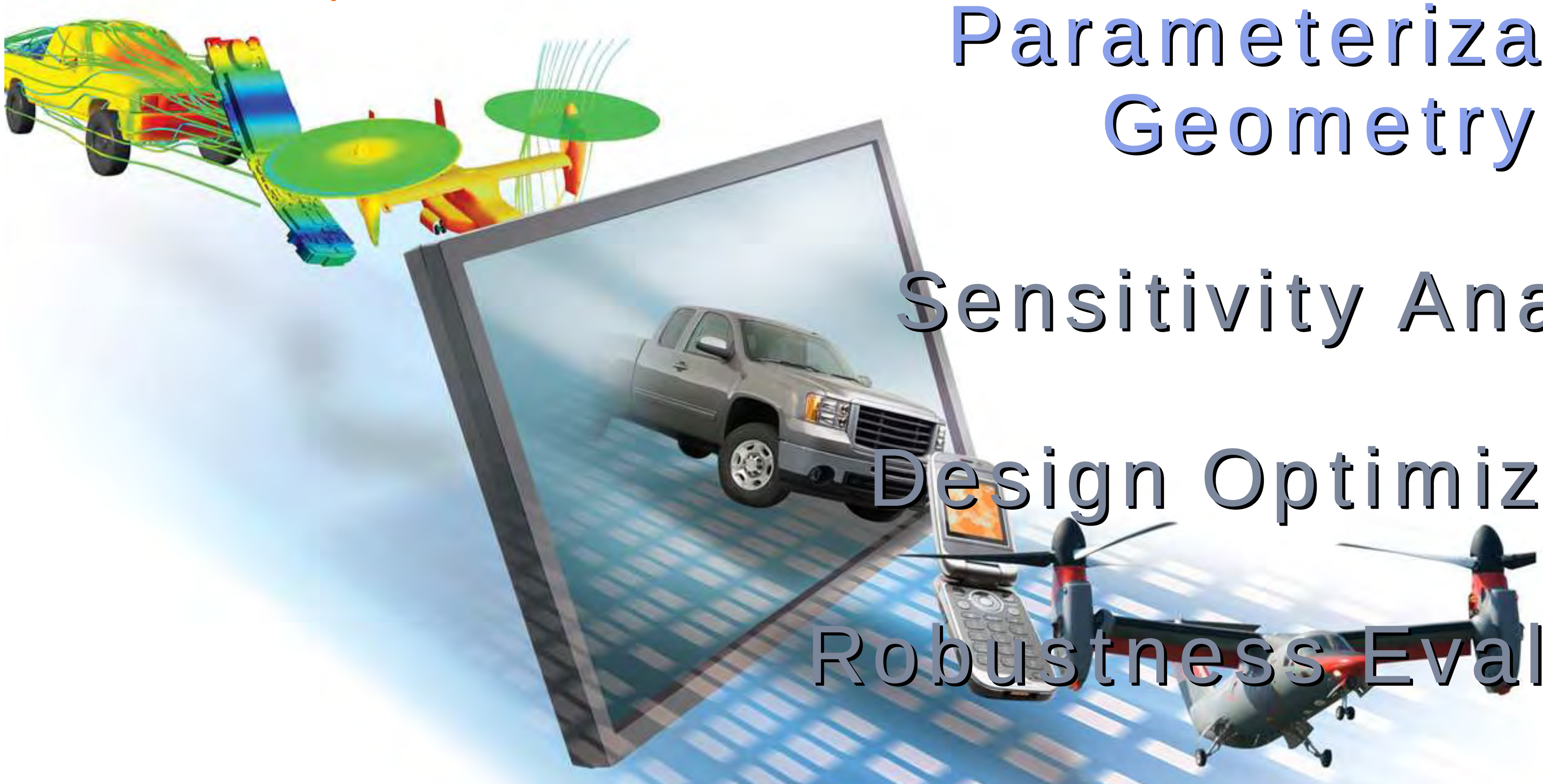





A Multi-Physics Design and Analysis System

- **Sensitivity**
- **Optimization**
- **Robustness**
- **Reliability**
- **Robust Design**

optiSLang

ANSYS
dynardo



Parameterization Geometry

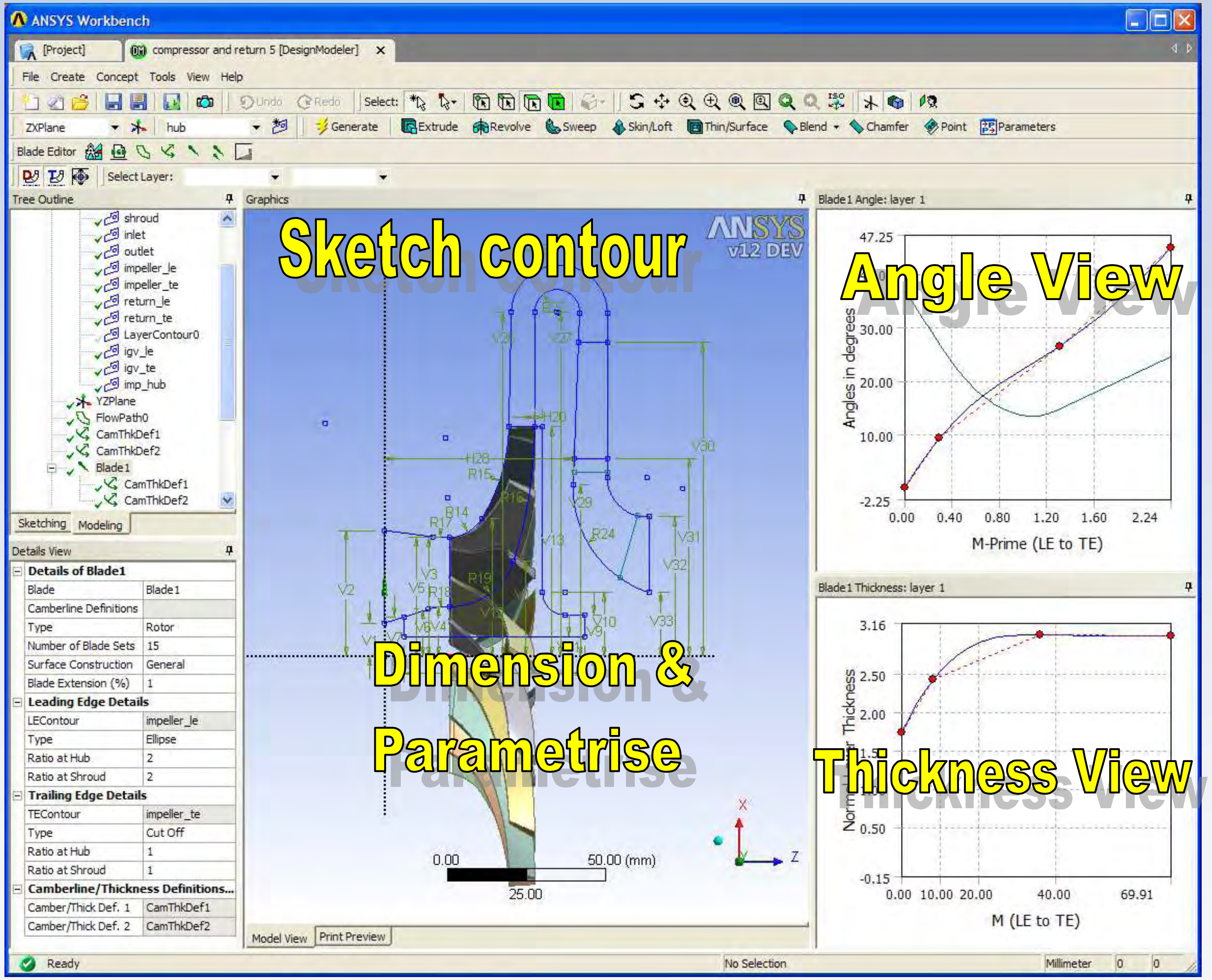
Sensitivity Analysis

Design Optimization

Robustness Evaluation

BladeModeler

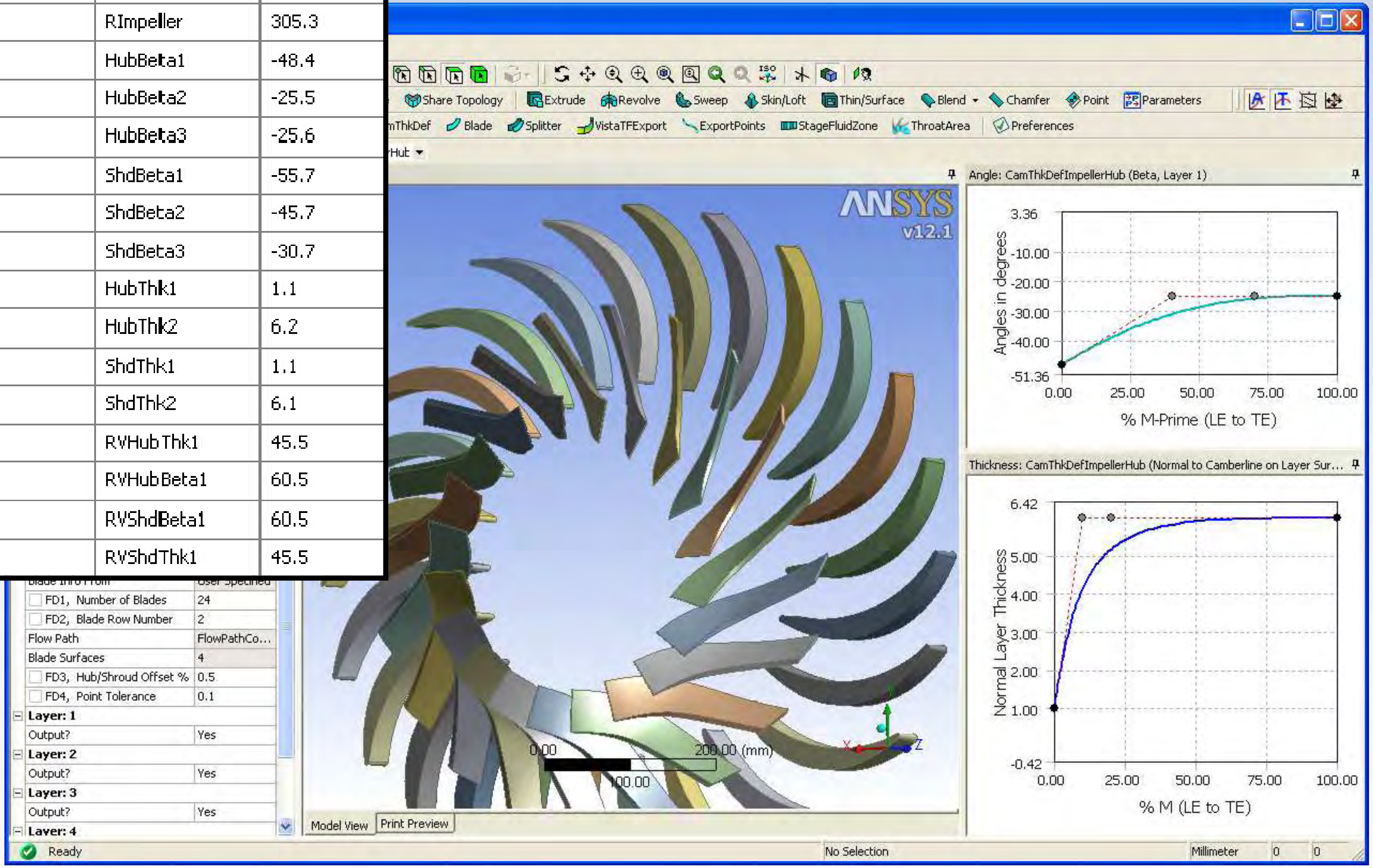
- Blade Design abilities in DesignModeler
- Angle/Thickness modifications in BladeEditor
- Multi-Stage Machines



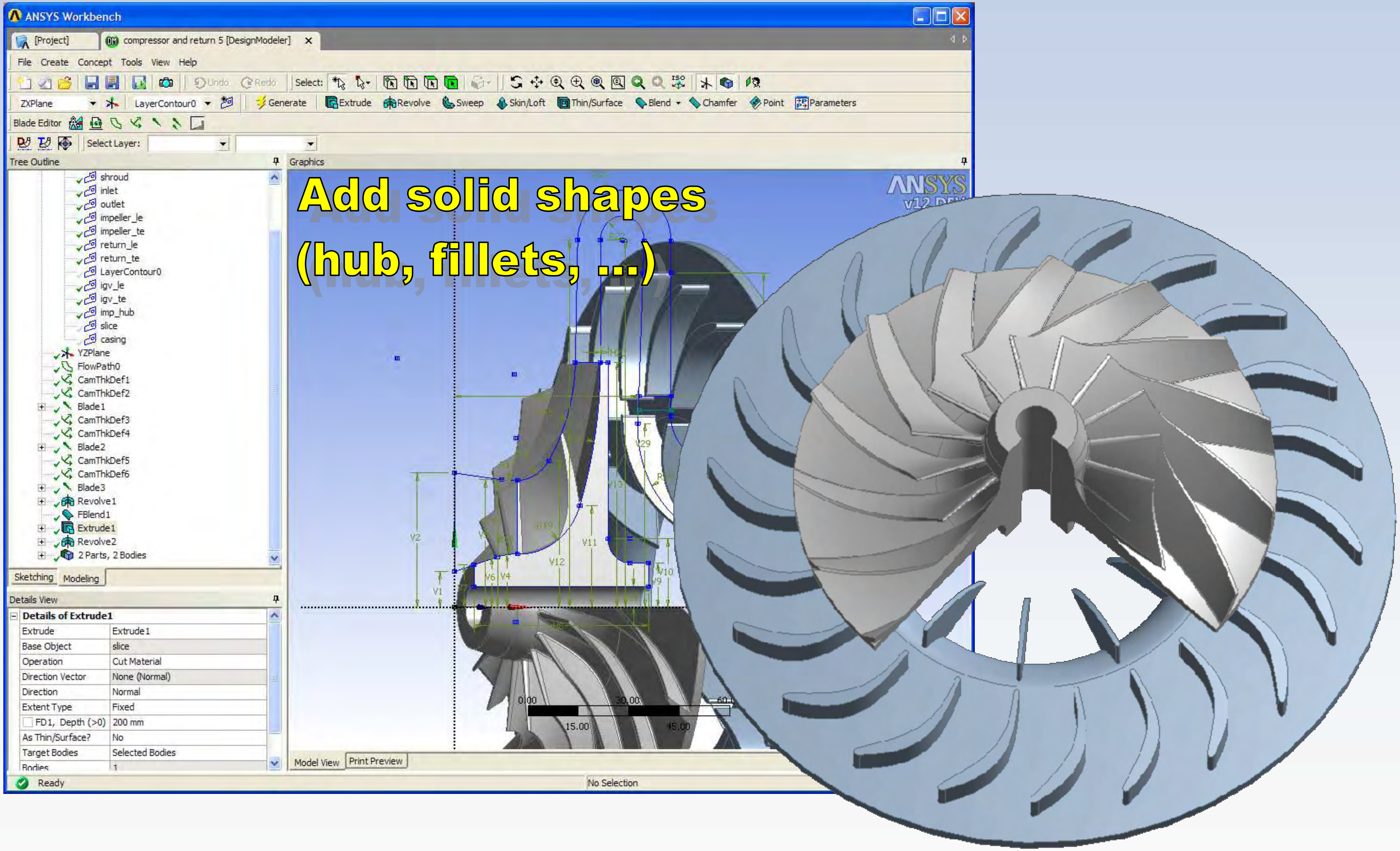
Geometry, Aerodynamic Design

Input Parameters		
P1	InletWidth	53.1
P8	ExitWidth	26.2
P9	RImpeller	305.3
P10	HubBeta1	-48.4
P11	HubBeta2	-25.5
P12	HubBeta3	-25.6
P13	ShdBeta1	-55.7
P14	ShdBeta2	-45.7
P15	ShdBeta3	-30.7
P16	HubThk1	1.1
P17	HubThk2	6.2
P18	ShdThk1	1.1
P19	ShdThk2	6.1
P21	RVHubThk1	45.5
P22	RVHubBeta1	60.5
P23	RVShdBeta1	60.5
P24	RVShdThk1	45.5

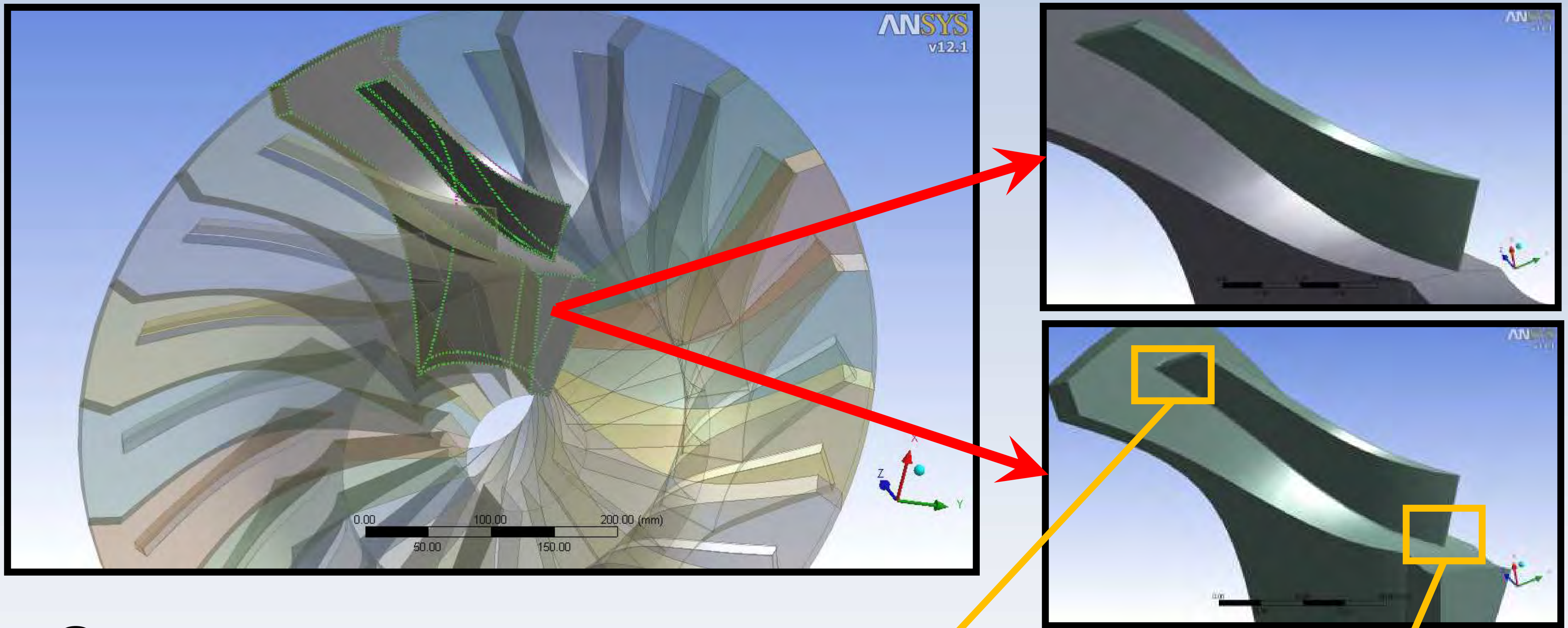
17 Geometry Parameter



3D Blade Design

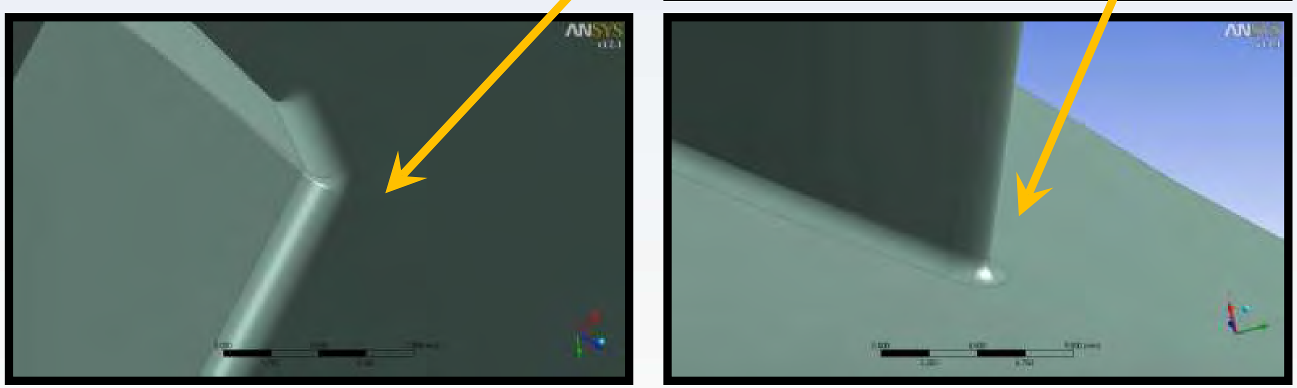


Geometry, Impeller



One sector

Model:
A, no blend
B, blend 1 mm

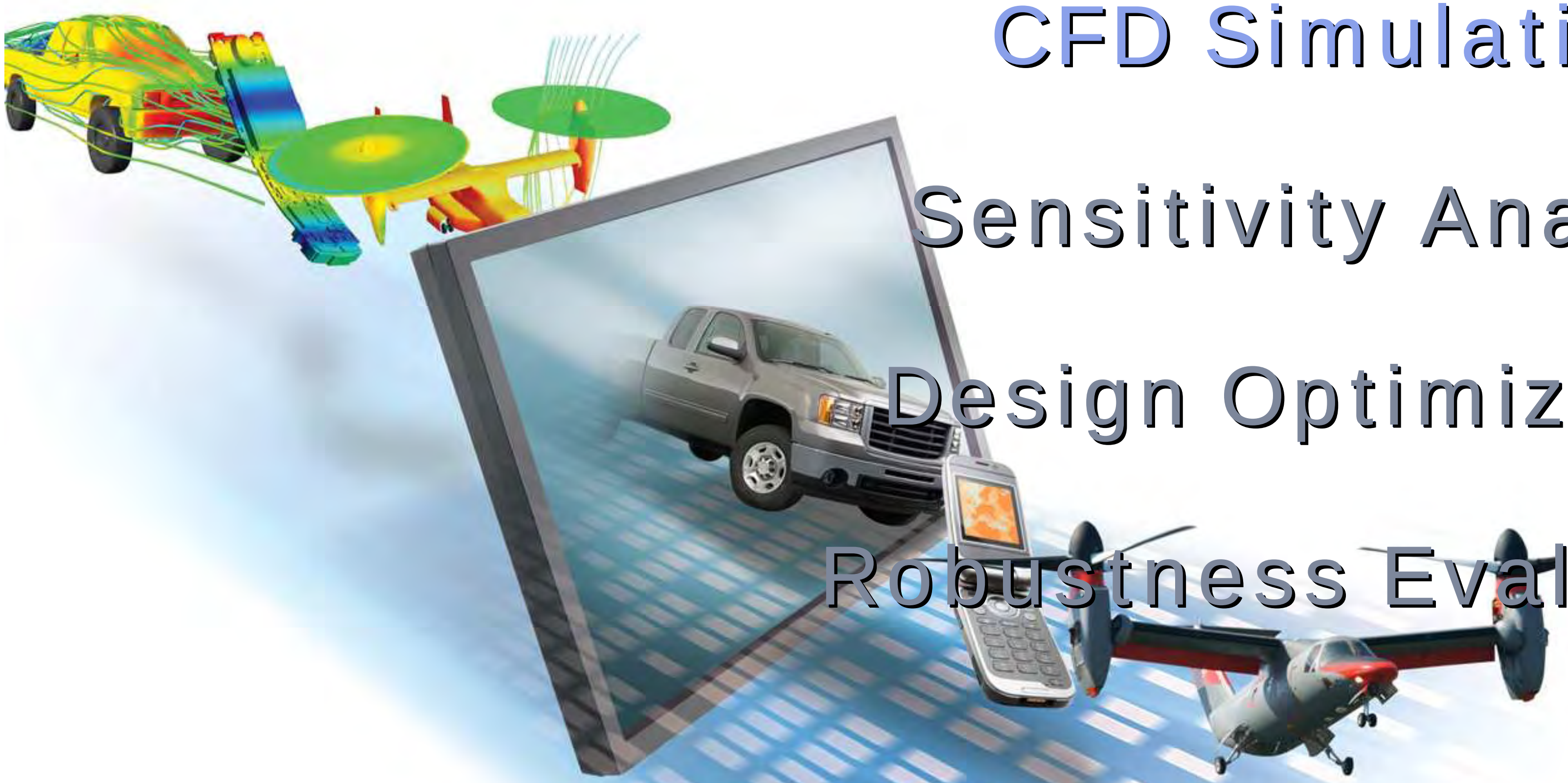


Parameterization
CFD Simulation

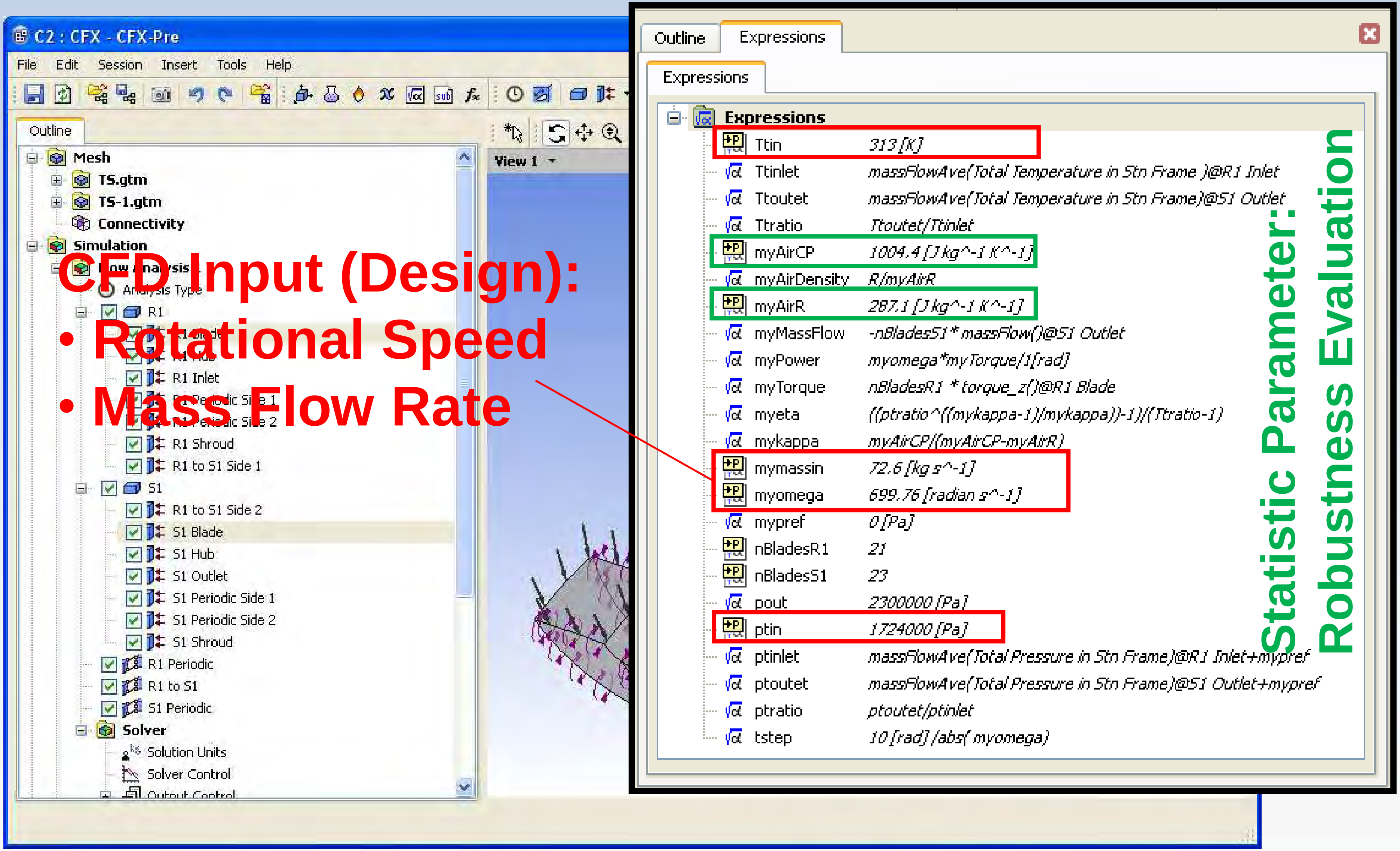
Sensitivity Analysis

Design Optimization

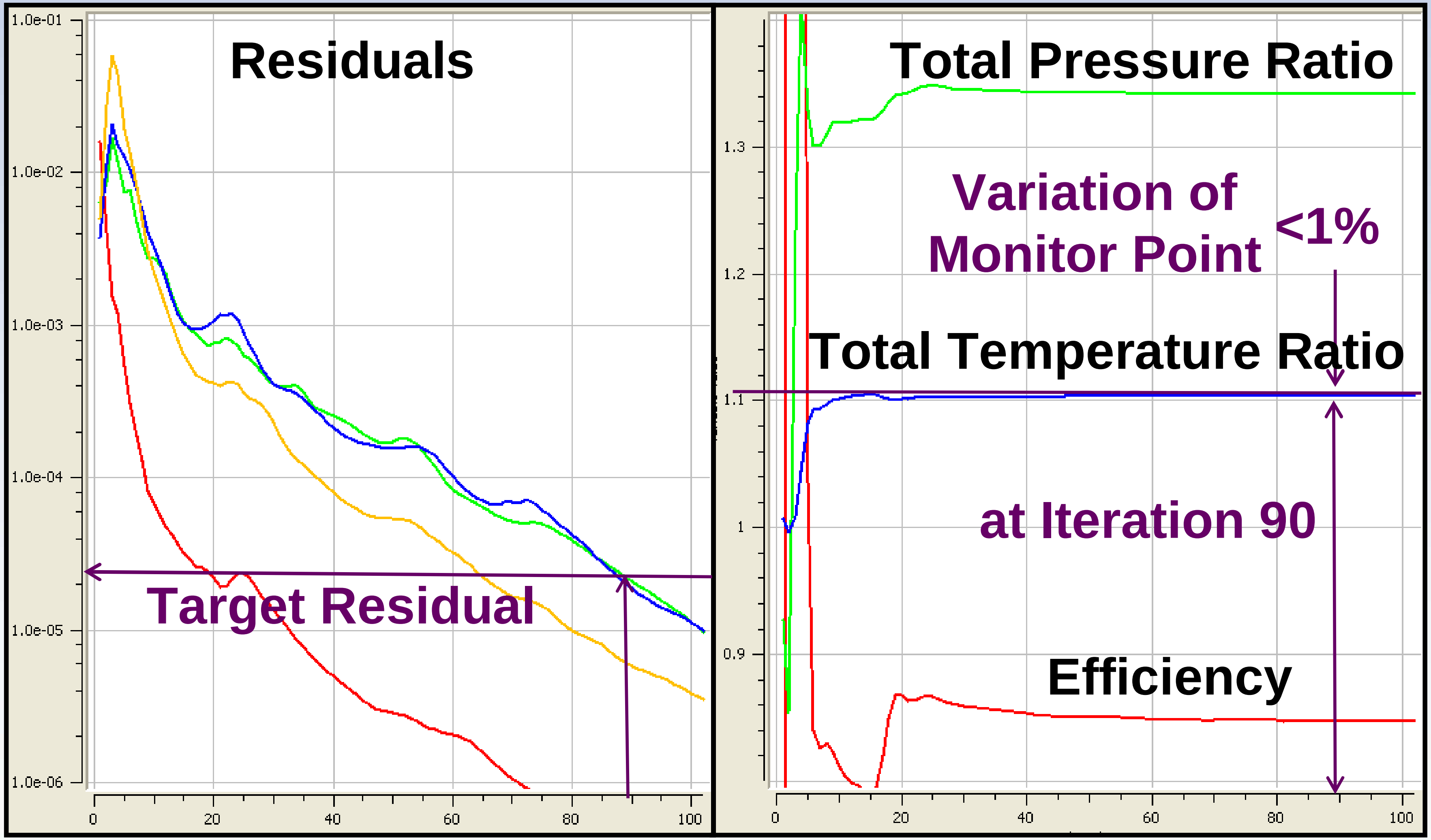
Robustness Evaluation



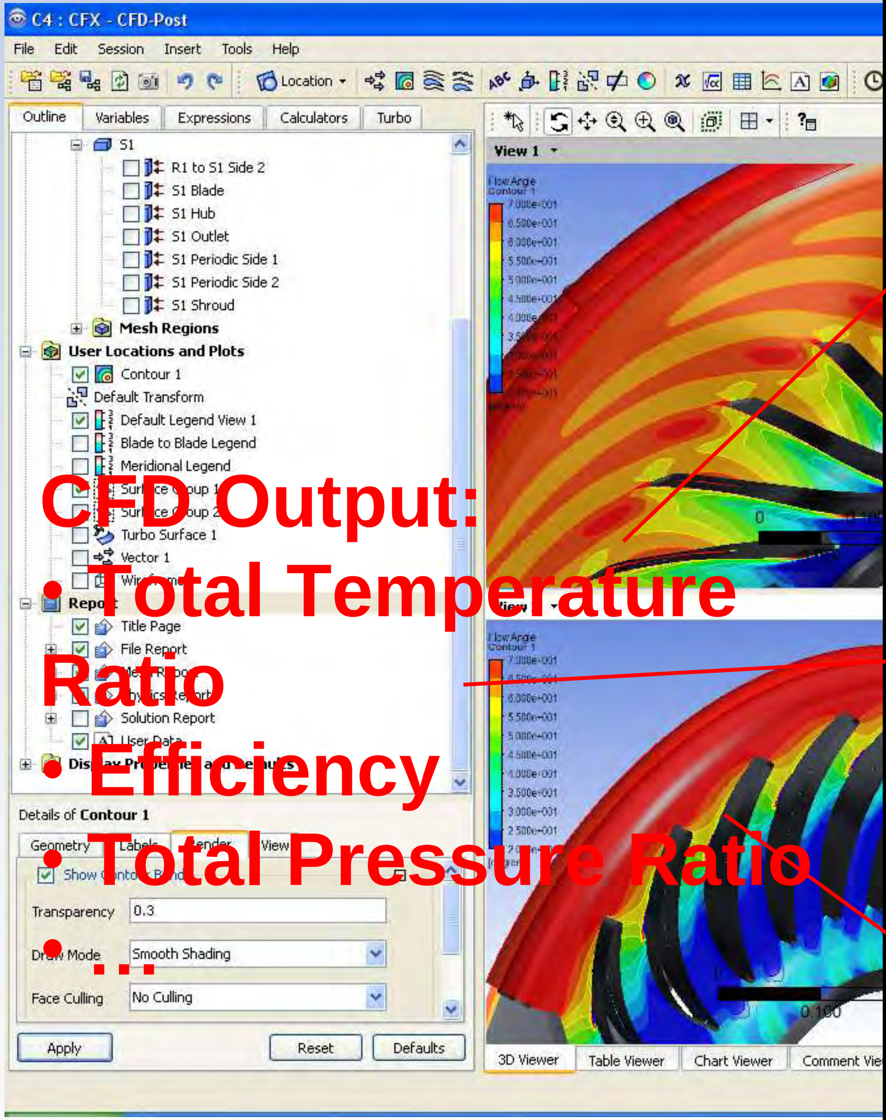
CFX Preprocessing



CFX Solver

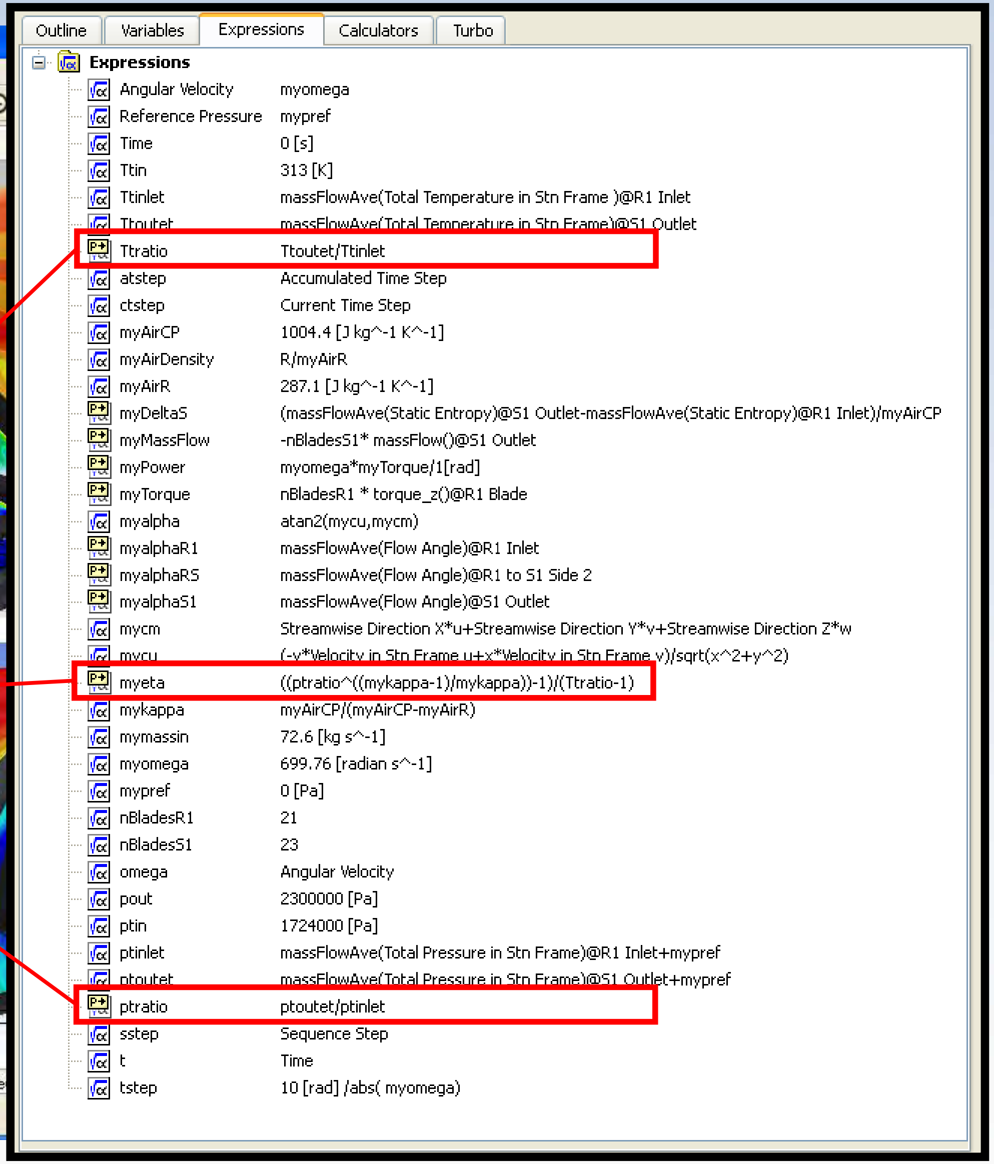

Residuals
1.0e-01
1.0e-02
1.0e-03
1.0e-04
1.0e-05
1.0e-06
0
20
40
60
80
100
Target Residual
Total Pressure Ratio
Variation of
Monitor Point
<1%
Total Temperature Ratio
at Iteration 90
Efficiency
1.3
1.2
1.1
1
0.9

CFX Postprocessing

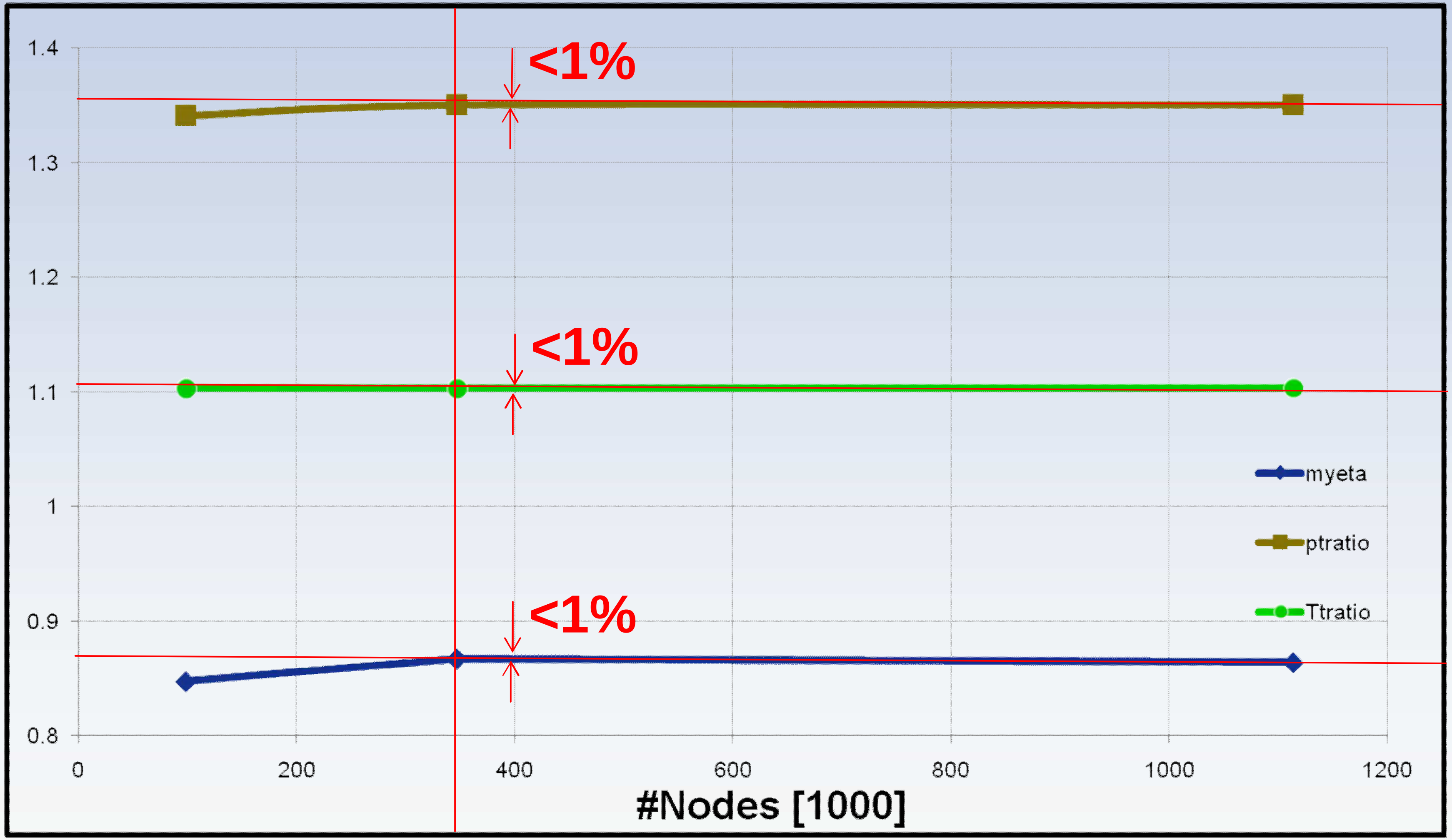


CFD Output:

- **Total Temperature Ratio**
- **Efficiency**
- **Total Pressure Ratio**
- **...**



CFX, Best Practice



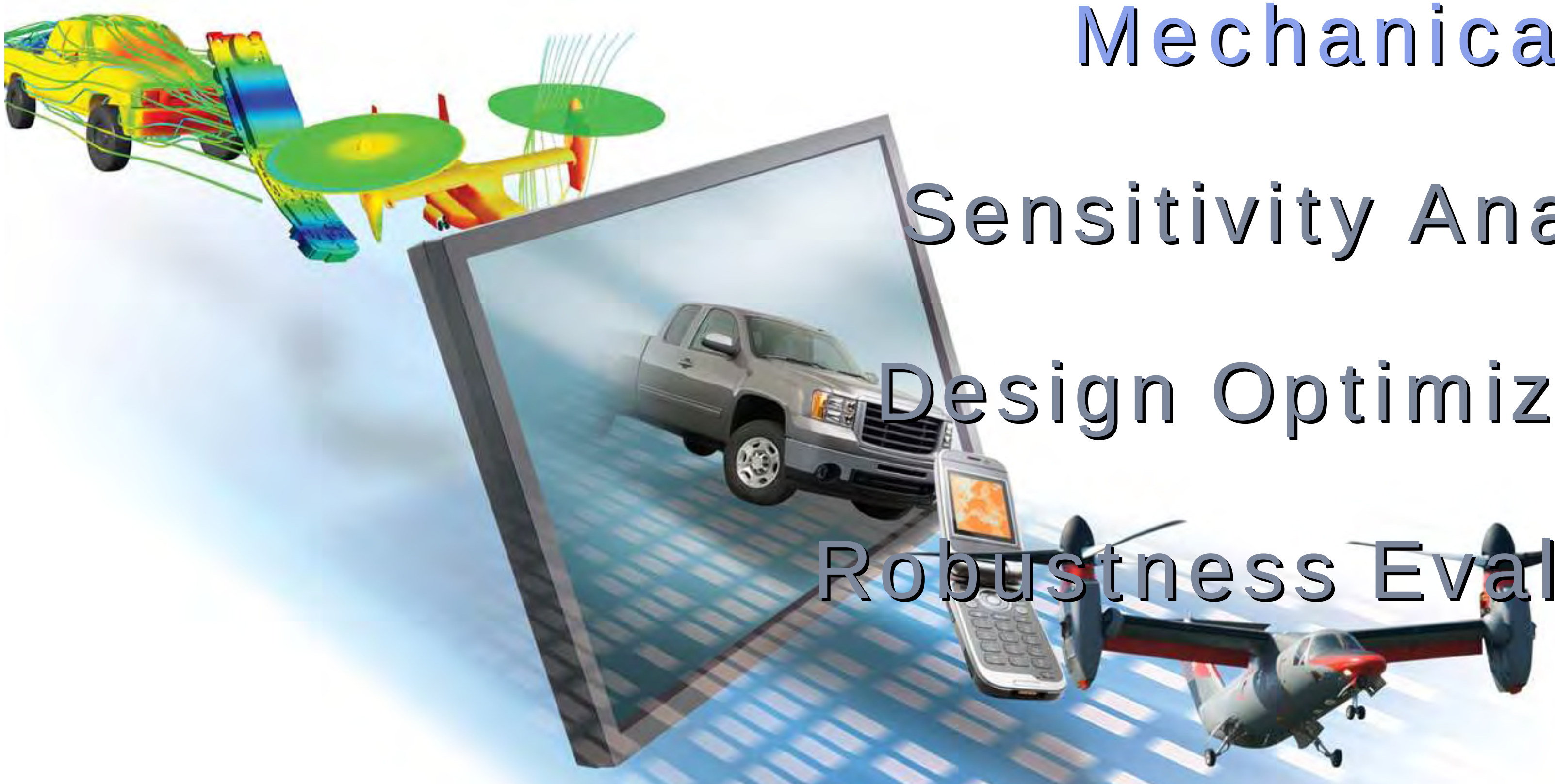
ANSYS dynardo

Parameterization Mechanical

Sensitivity Analysis

Design Optimization

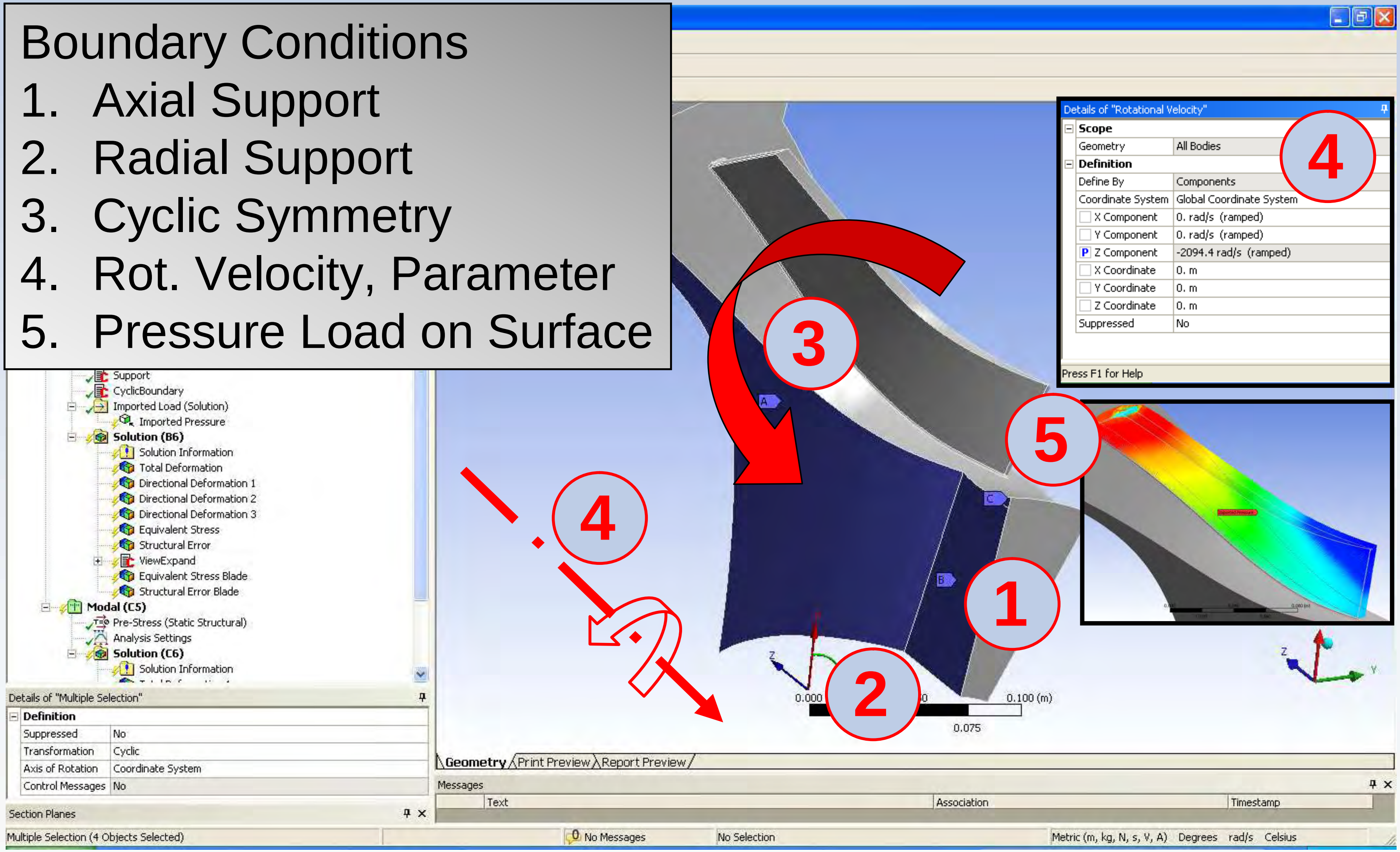
Robustness Evaluation



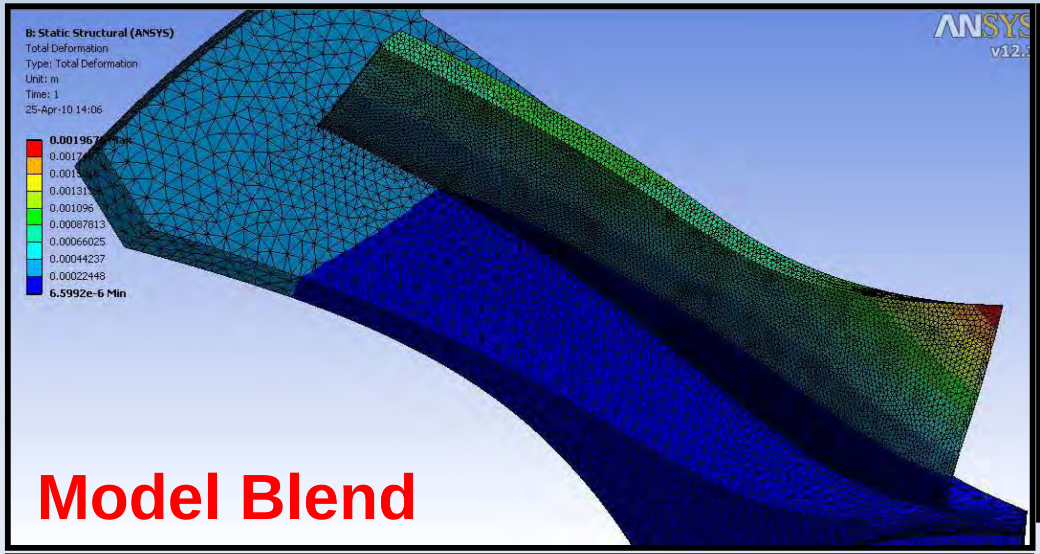
Boundary Conditions and Loads

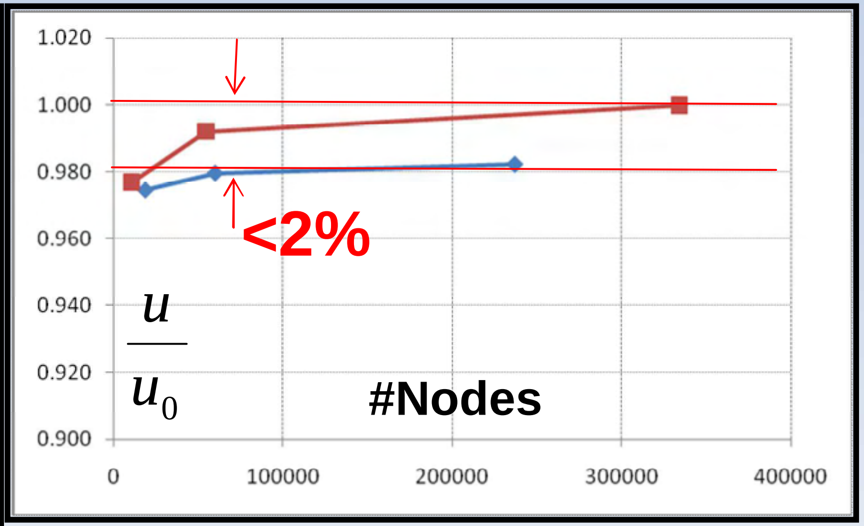
Boundary Conditions

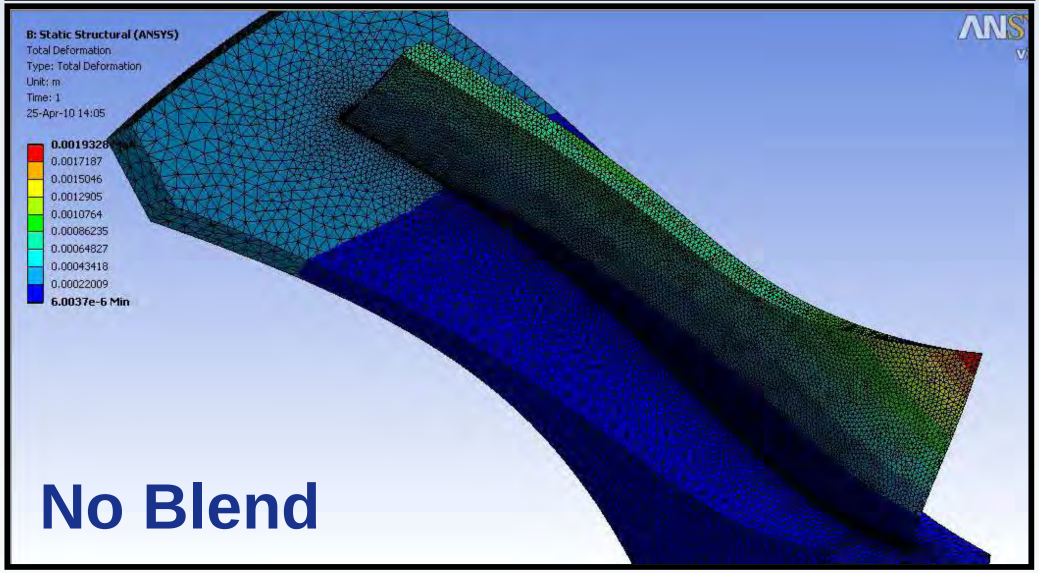
1. Axial Support
2. Radial Support
3. Cyclic Symmetry
4. Rot. Velocity, Parameter
5. Pressure Load on Surface



Mechanical, Displacement

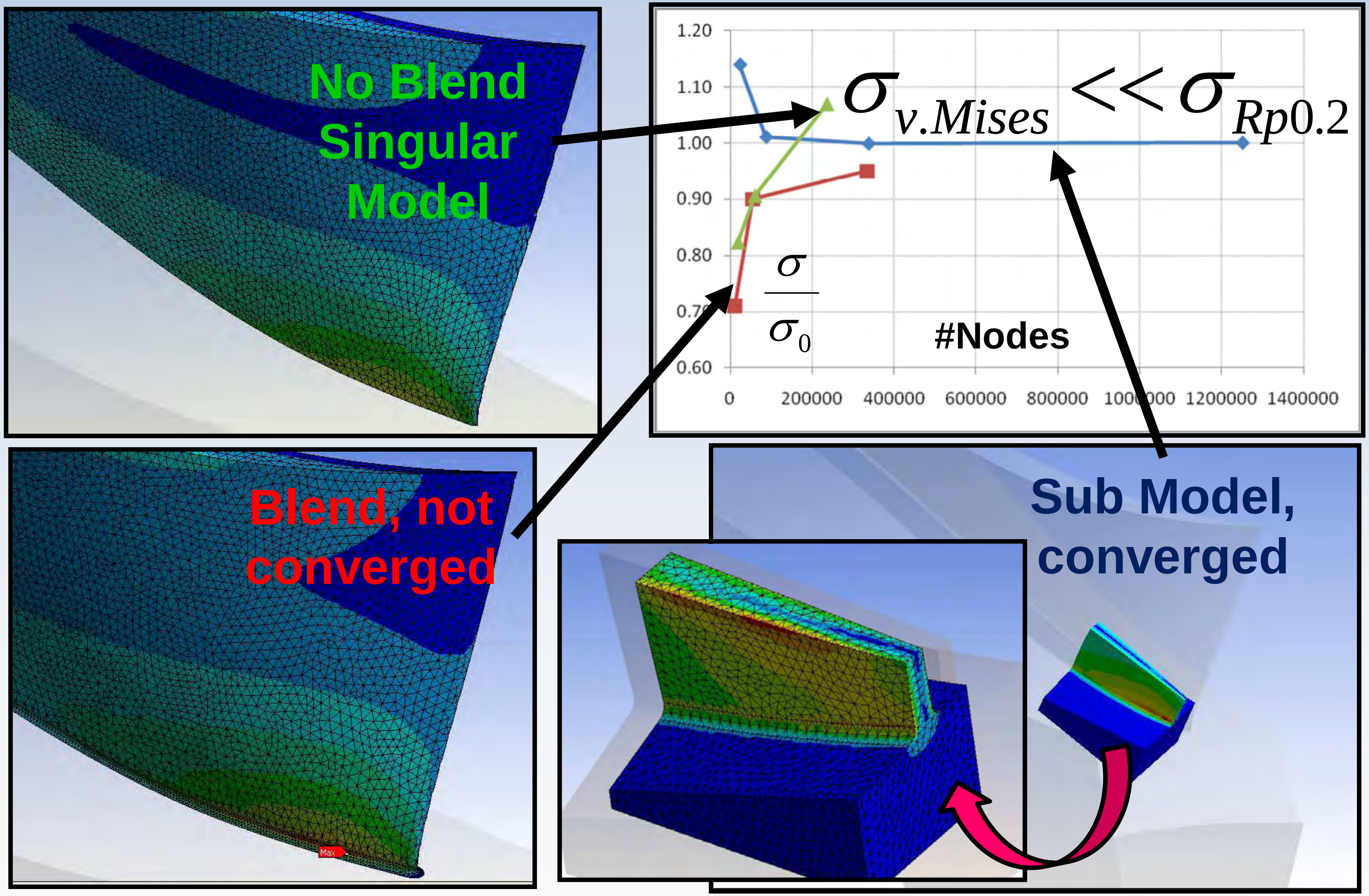




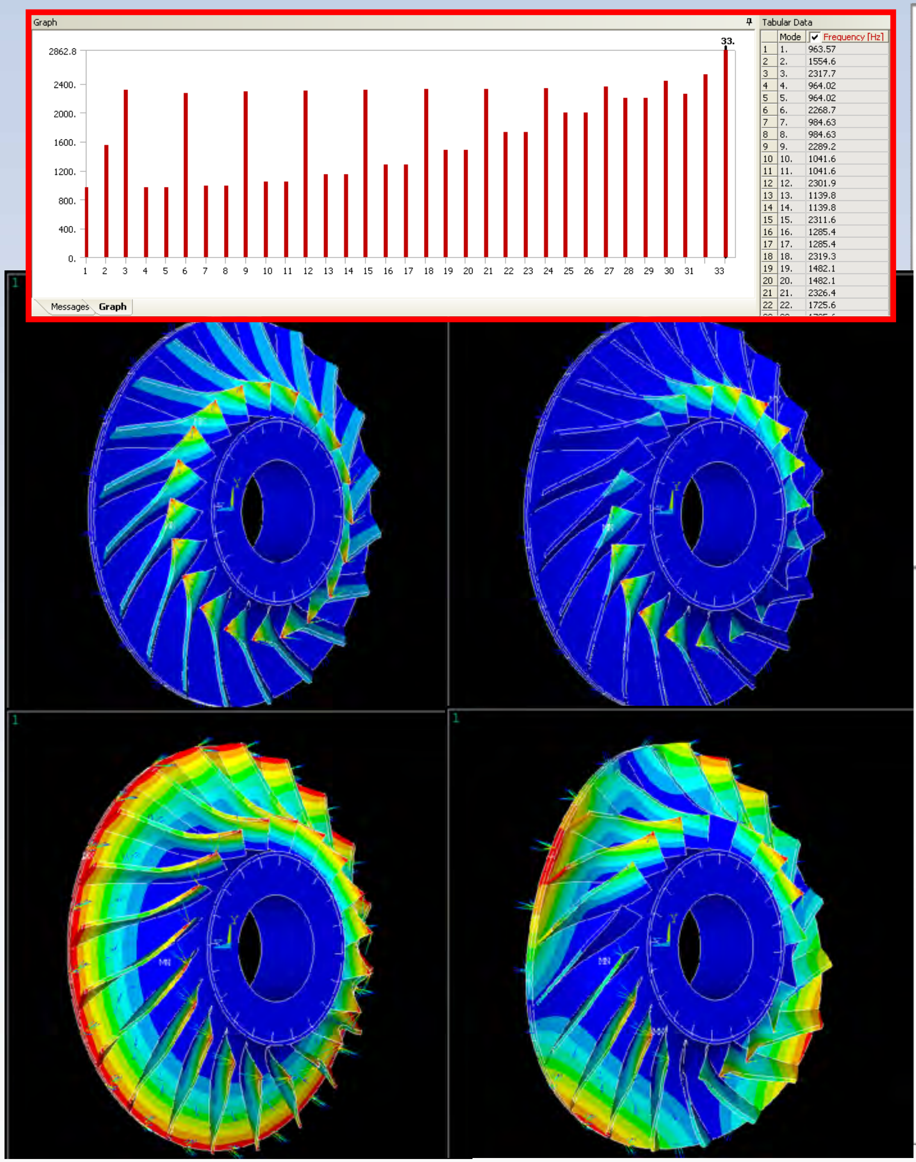


Blend has minor influence on displacement

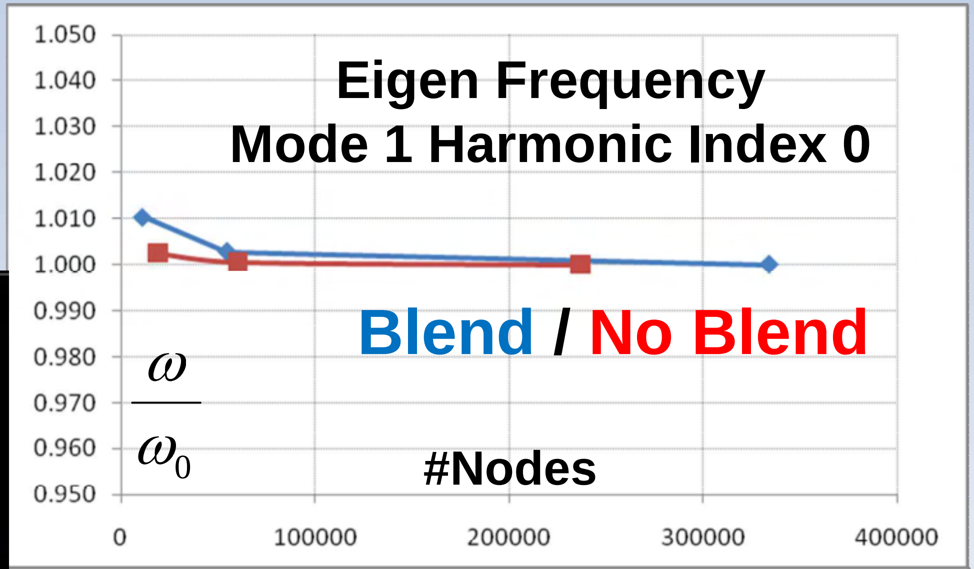
Mechanical, Stress

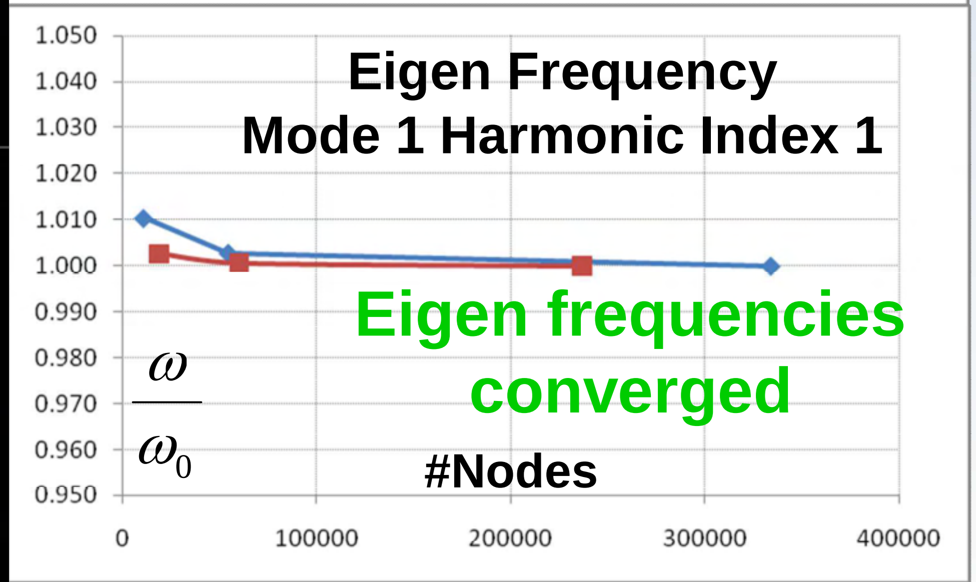


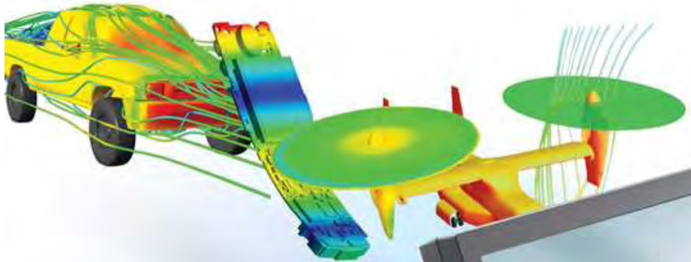
Mechanical, Modal Analysis



	Mode	Frequency [Hz]
1	1.	963.57
2	2.	1554.6
3	3.	2317.7
4	4.	964.02
5	5.	964.02
6	6.	2268.7
7	7.	984.63
8	8.	984.63
9	9.	2289.2
10	10.	1041.6
11	11.	1041.6
12	12.	2301.9
13	13.	1139.8
14	14.	1139.8
15	15.	2311.6
16	16.	1285.4
17	17.	1285.4
18	18.	2319.3
19	19.	1482.1
20	20.	1482.1
21	21.	2326.4
22	22.	1725.6







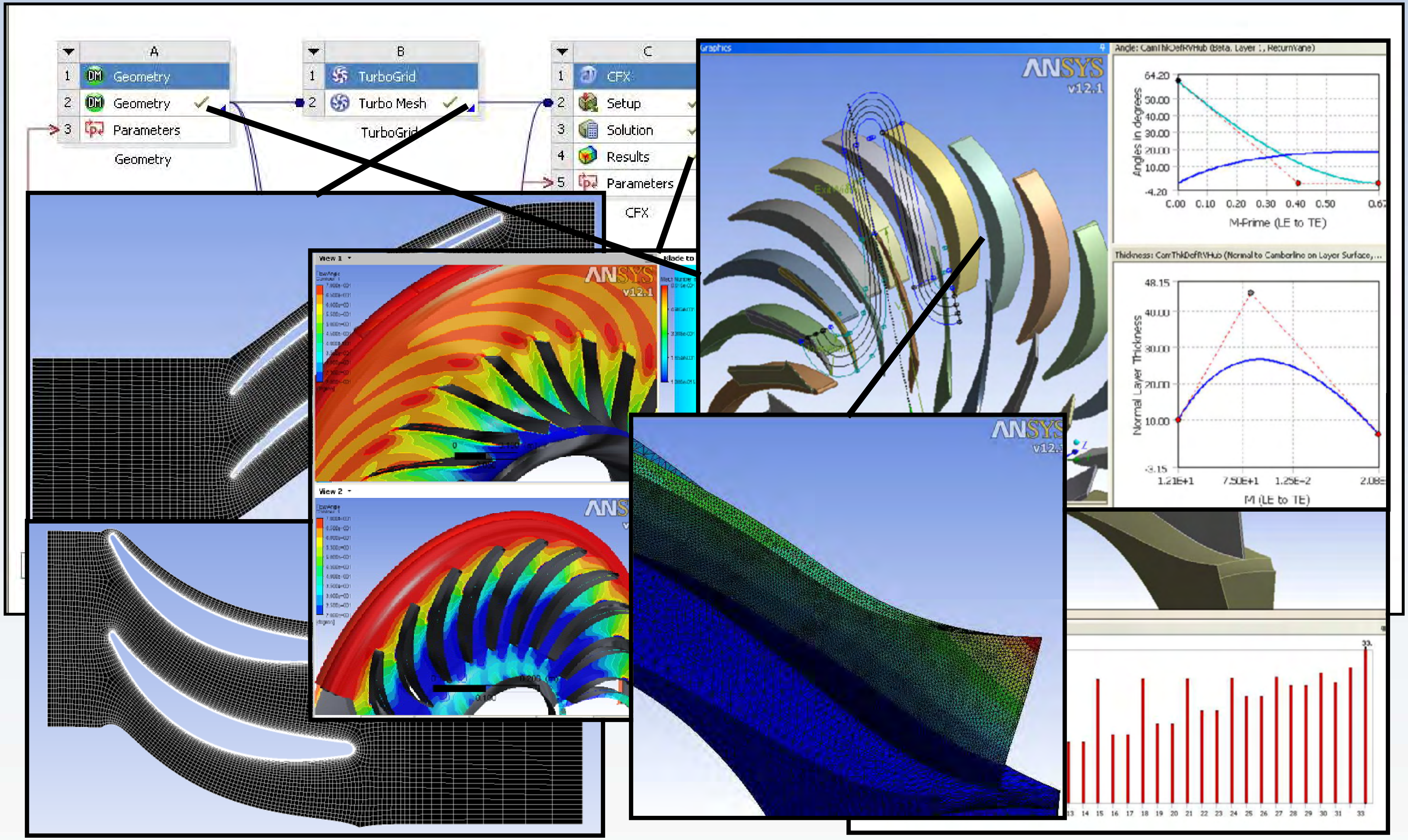
Parameterization Process

Sensitivity Analysis

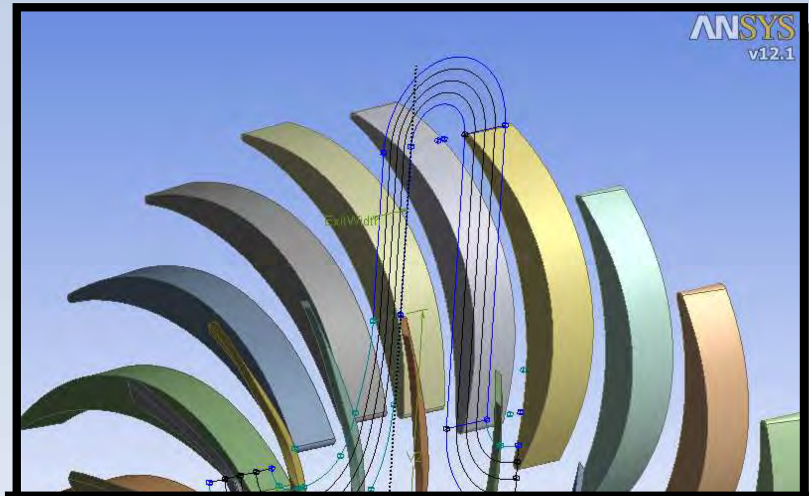
Design Optimization

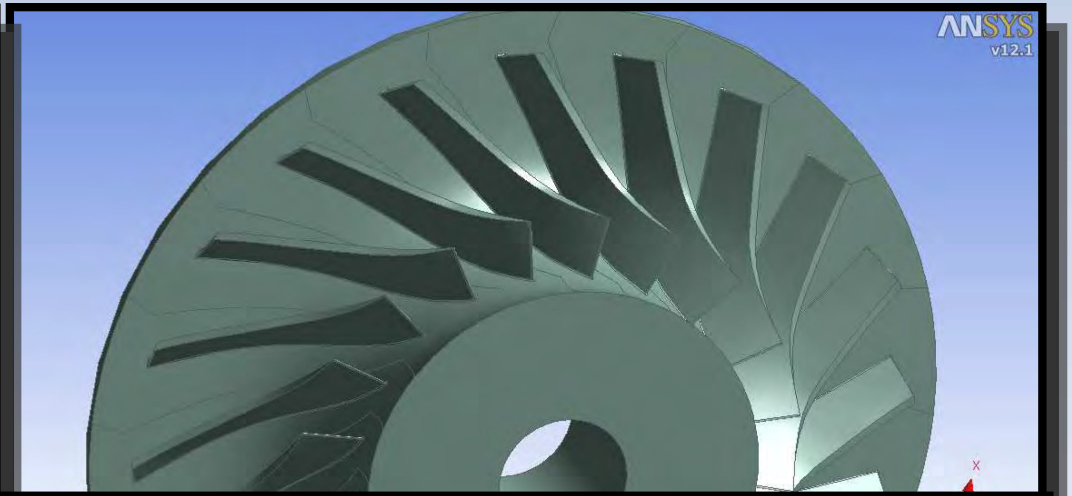
Robustness Evaluation

Parametric Process



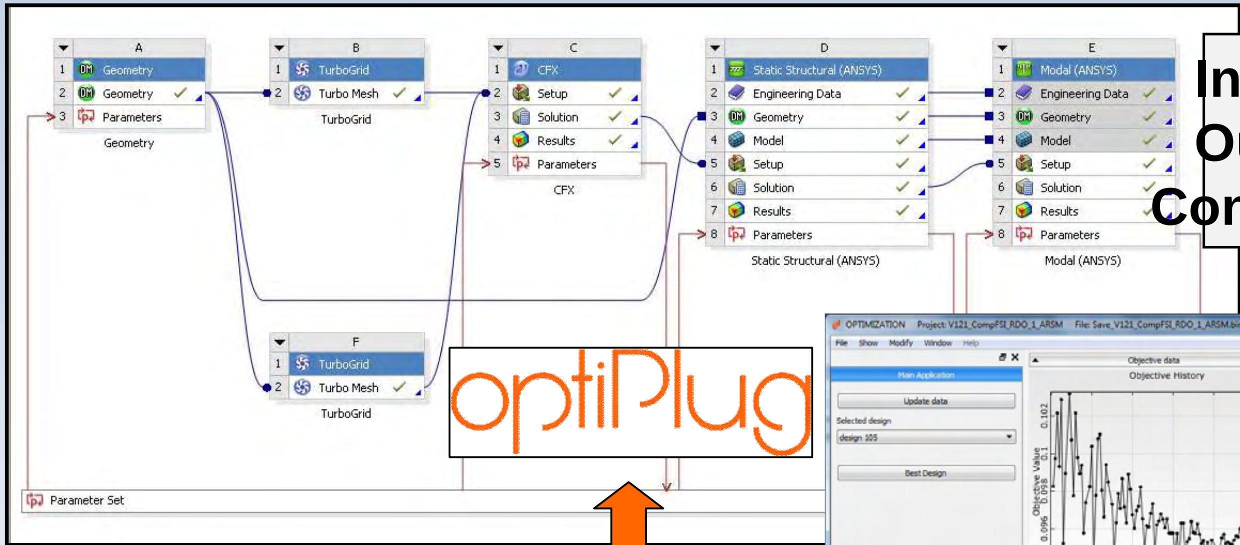
Optimization Objective



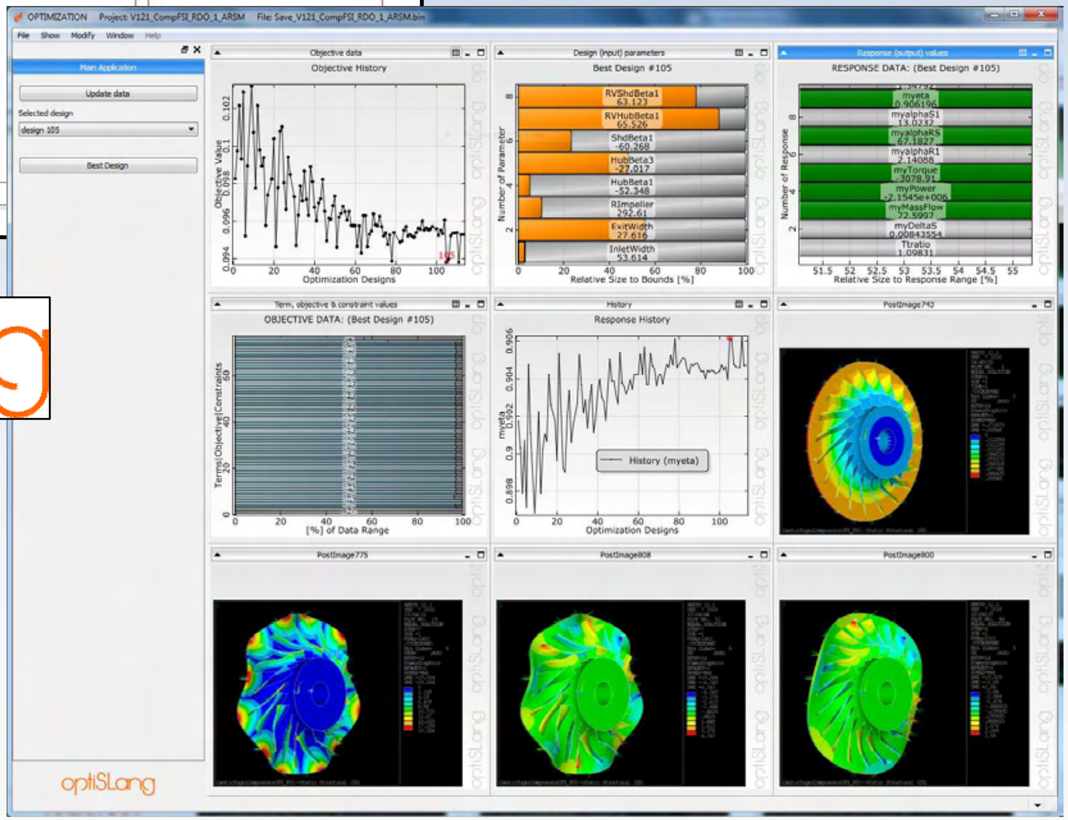


Defined Operating Point:
Mass Flow Rate 72.6 kg/s
Rotational Velocity Ω=6644 rev/min
Total Pressure Ratio π=1.35±0.01, Objective
Maximal Efficiency η=max, Objective
No Resonance: $\Omega \neq \omega_i$

Parametric Process



Input Parameter	21
Output Parameter	43
Constraints	68



Parametric Workflow for Multi Physic Application

- Extended solver support
- Embedded analysis tool
- Without user interaction

ANSYS
dynardo

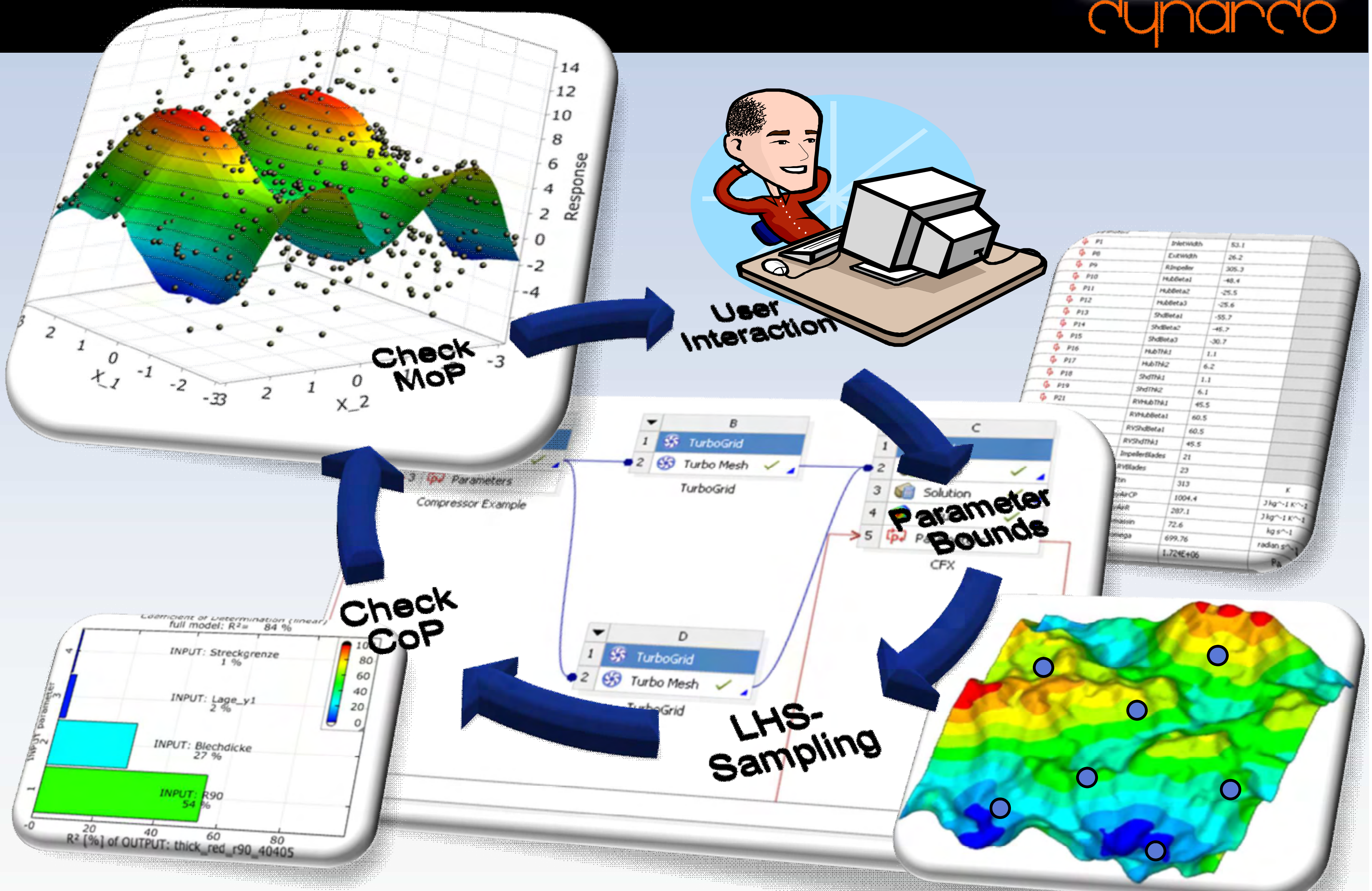
Parameterization

Sensitivity Analysis

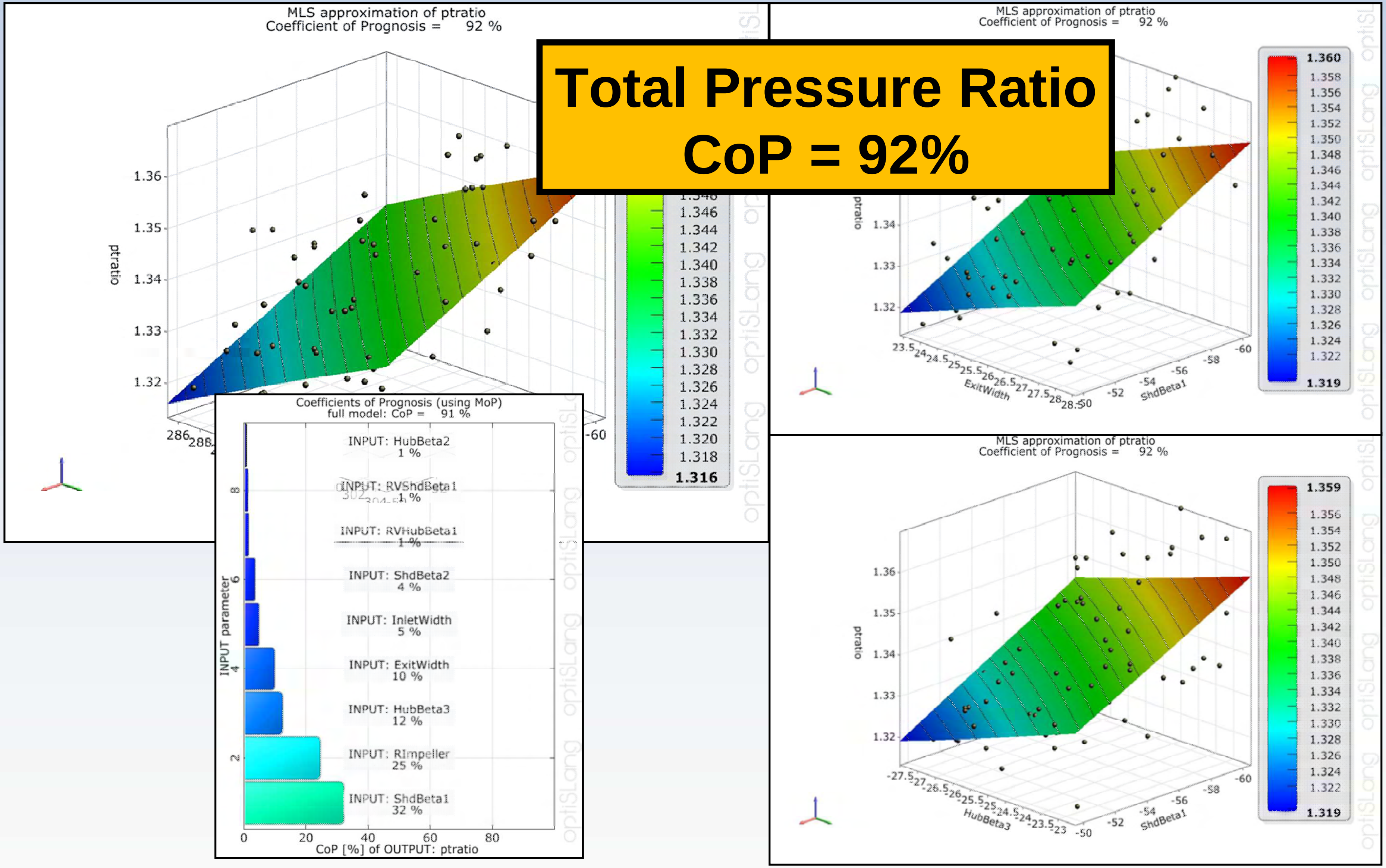
Design Optimization

Robustness Evaluation

Sensitivity Analysis



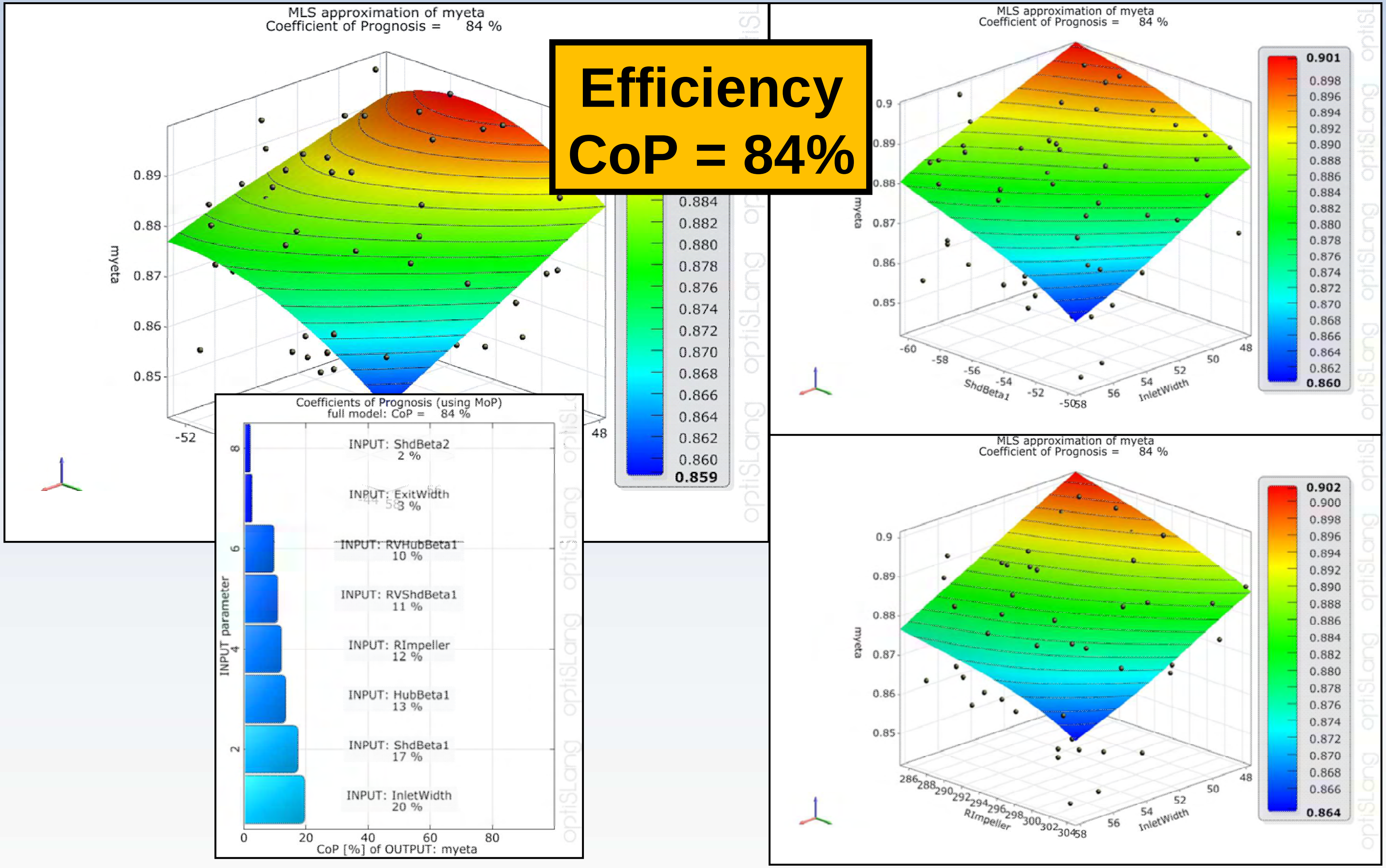
Meta-Model of Best Prognosis



Total Pressure Ratio
CoP = 92%

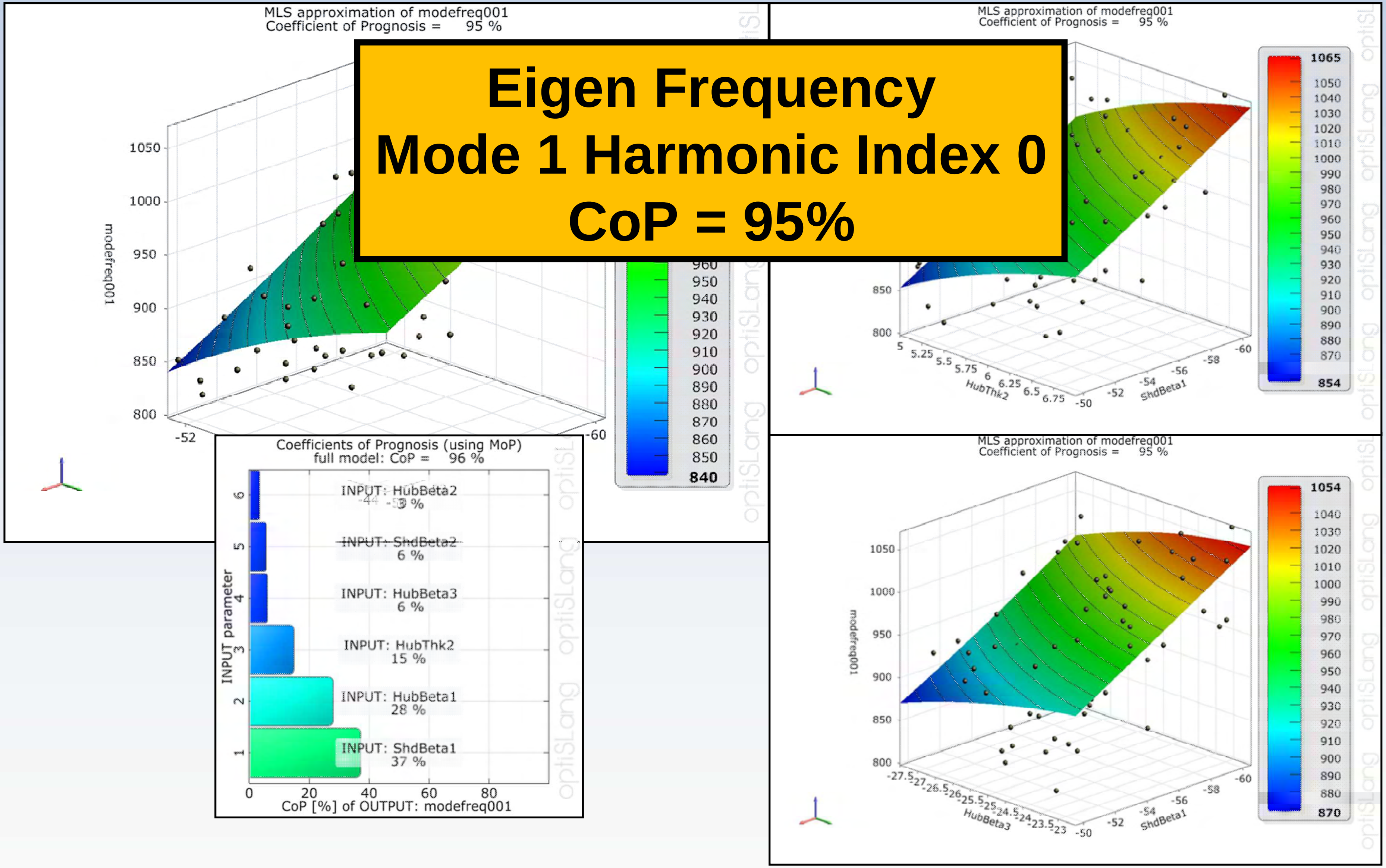
Meta-Model of Best Prognosis

Efficiency
CoP = 84%



Meta-Model of Best Prognosis

Eigen Frequency
Mode 1 Harmonic Index 0
CoP = 95%



Parameterization

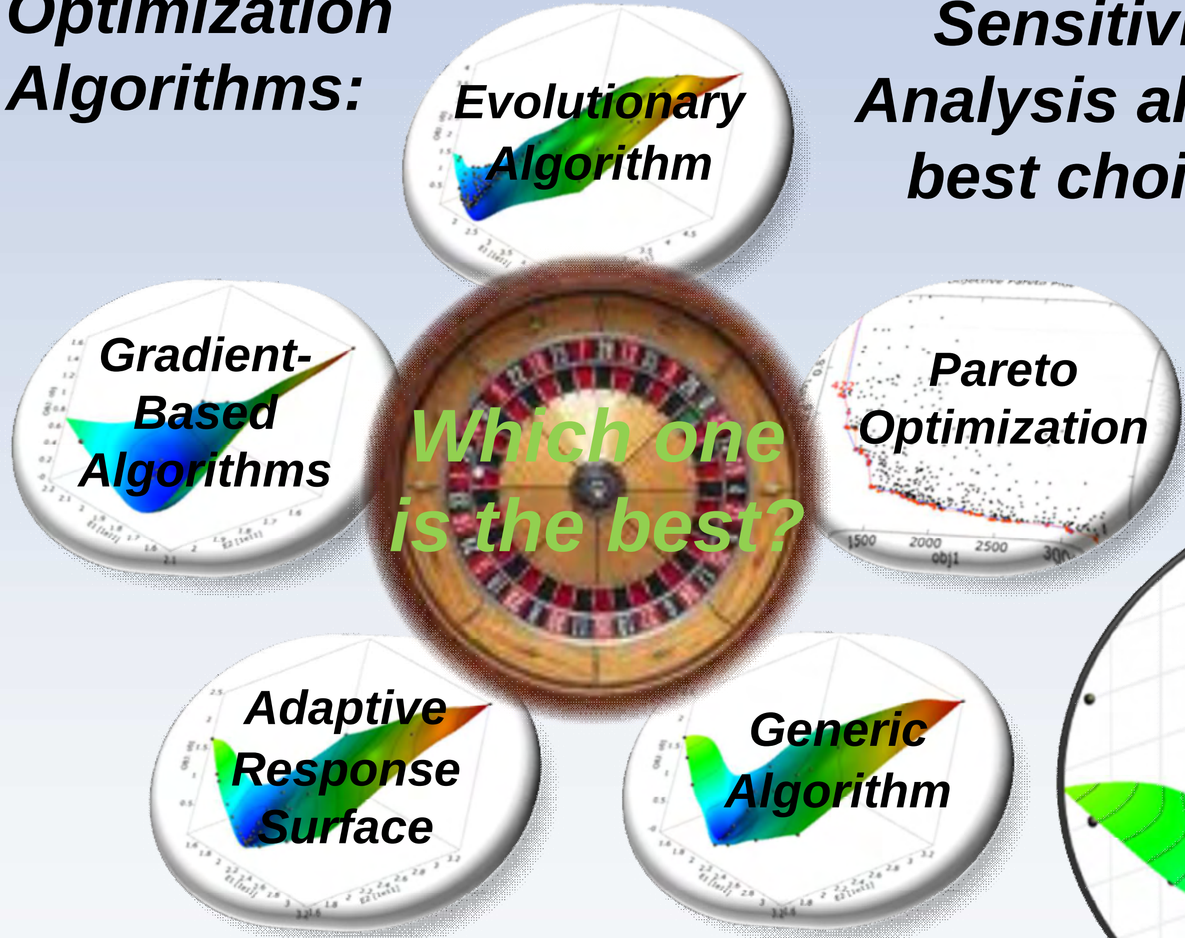
Sensitivity Analysis

Design Optimization

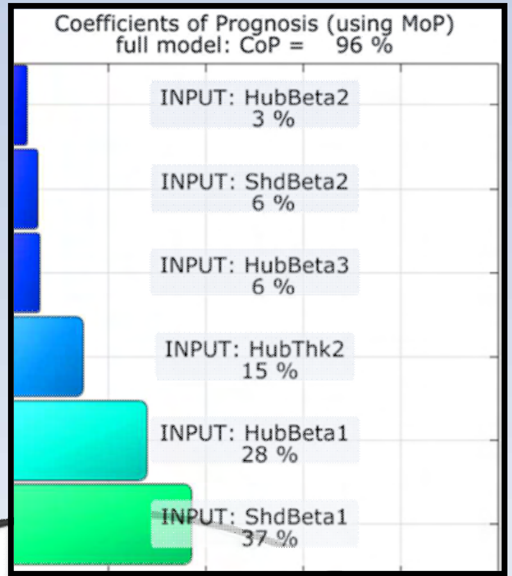
Robustness Evaluation

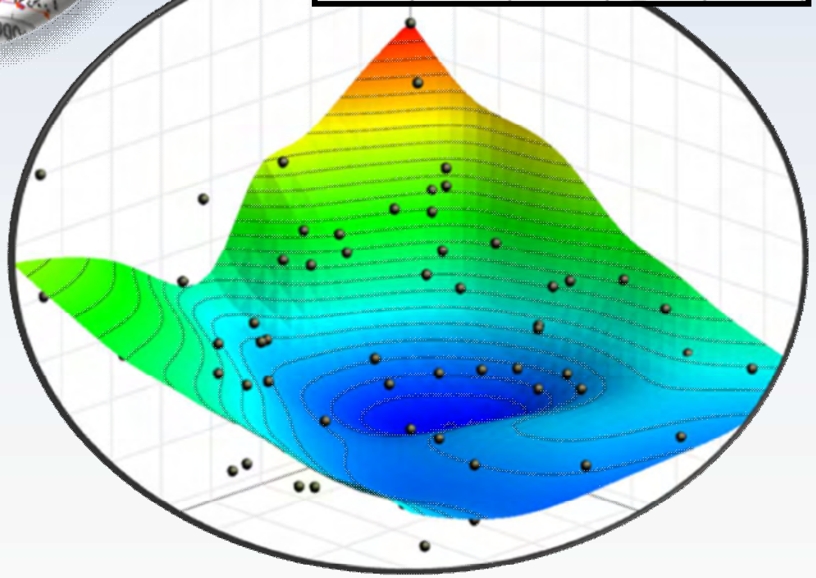
Design Optimization

Optimization Algorithms:



Sensitivity Analysis allows best choice!

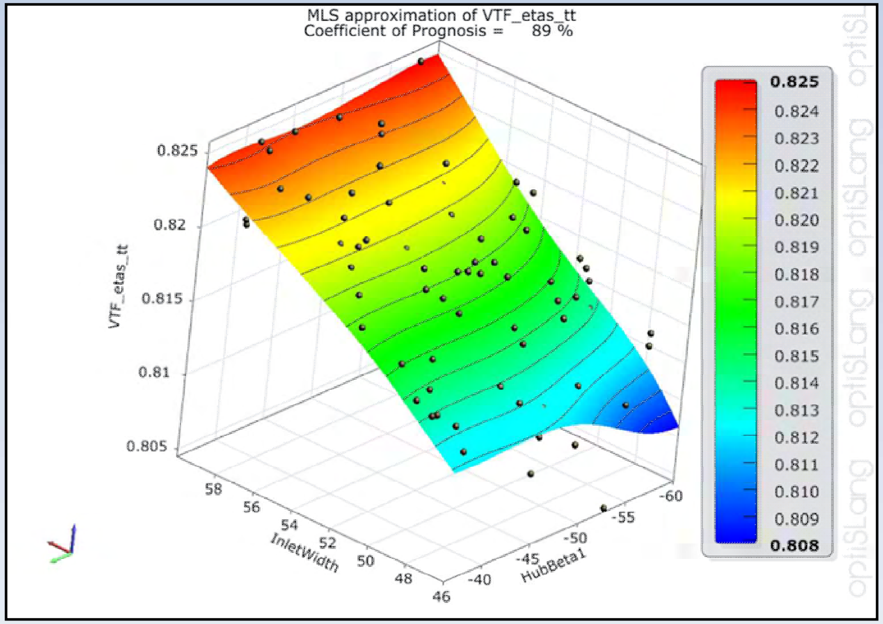




Optimization Strategy

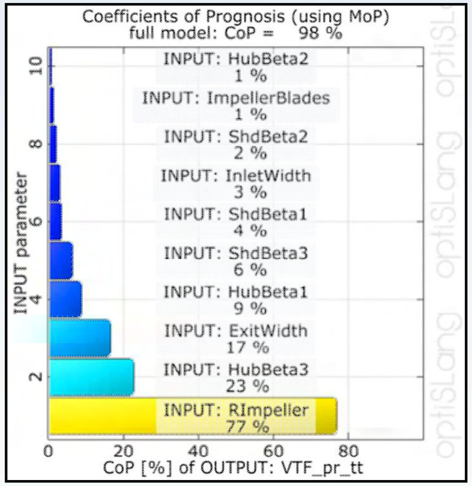
Sensitivity Analysis

- Shows Potential
- Indicates global optimum
- Parameter reduction
- Modify Parameter Space



Strategy:

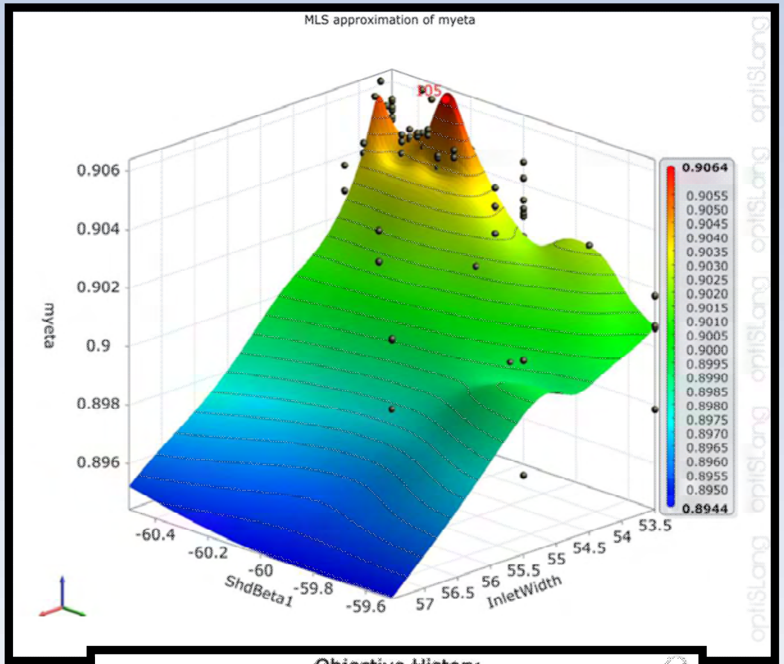
- **Pre-optimization in sub space, ARSM**
- **Local improvement, EA (full space)**
- **Start design(s) from ARSM**

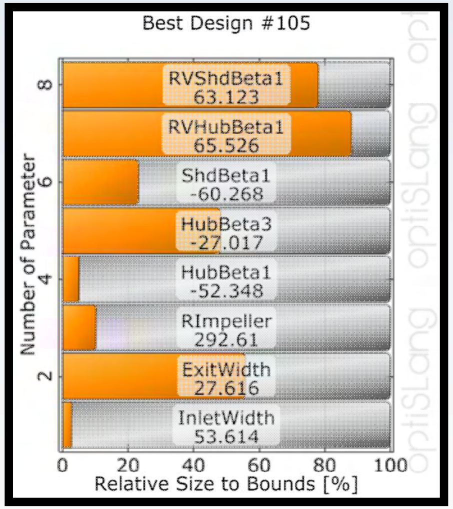


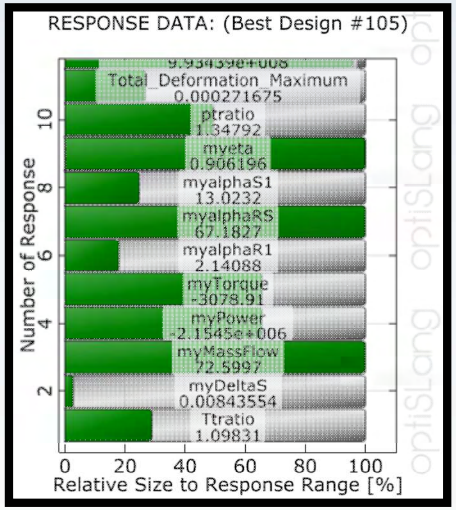
Adaptive Response Surface

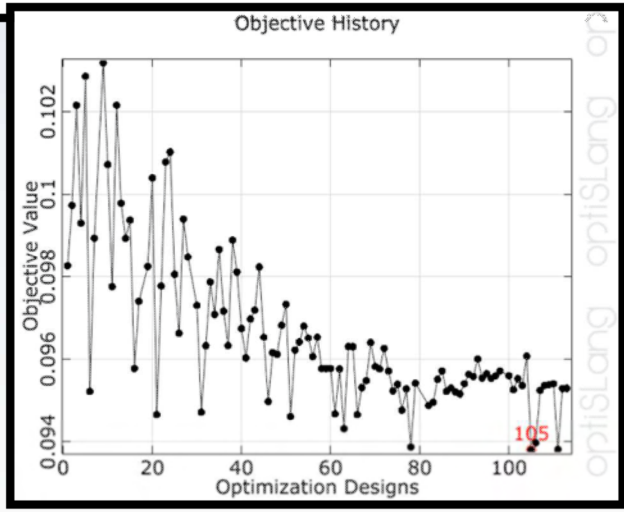
ARSM with 8 Parameter leads to better design:

	SA	ARSM
Total Pressure Ratio	**1.3497**	**1.3479**
Efficiency [%]	**89.15**	**90.62**
#Designs	**100**	**105**





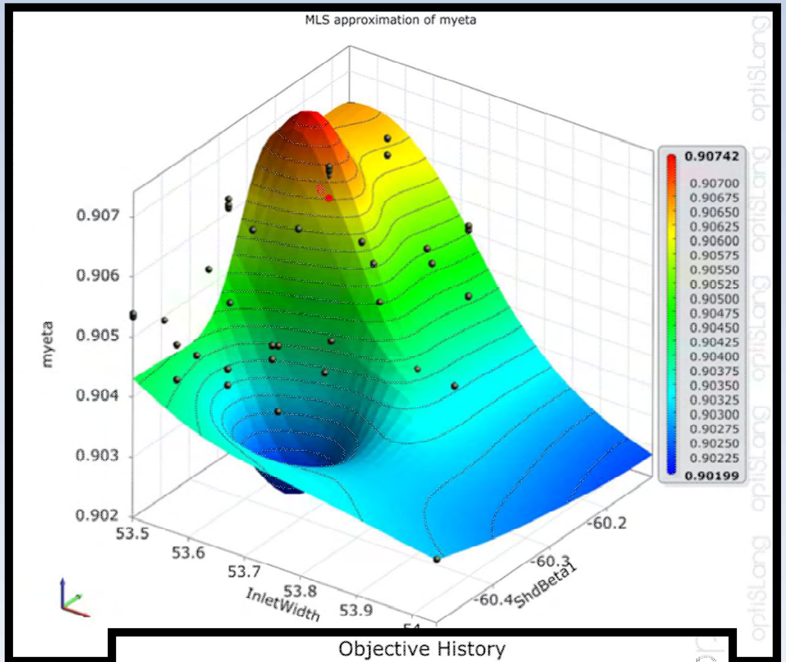


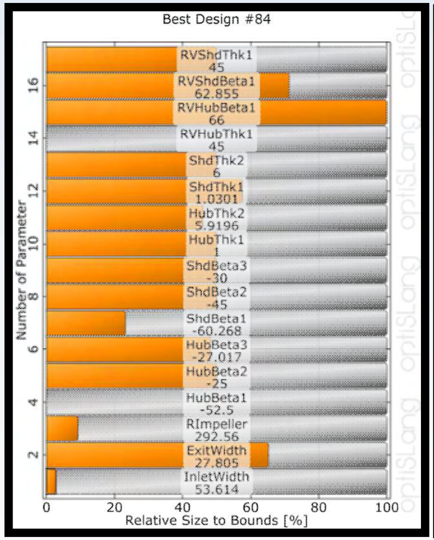


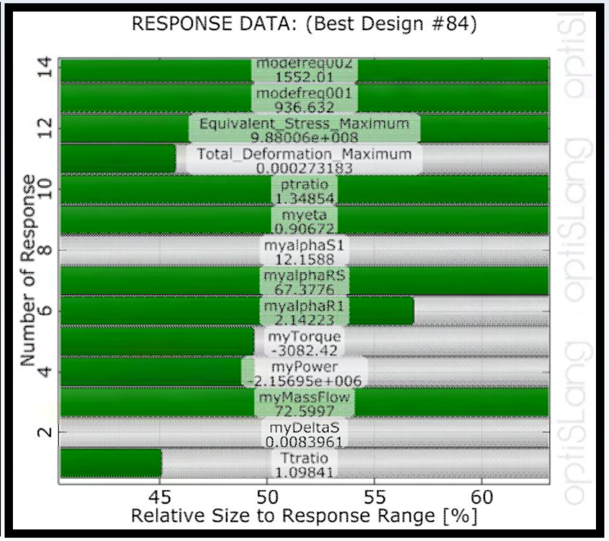
Evolutionary Algorithm

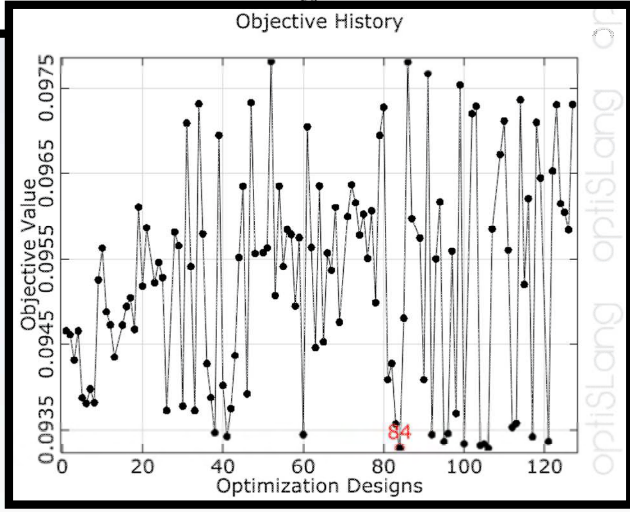
EA with 17 Parameter leads to further improvement:

	ARSM	EA
Total Press. Ratio	**1.3479**	**1.3485**
Efficiency [%]	**90.62**	**90.67**
#Designs	**105**	**84**





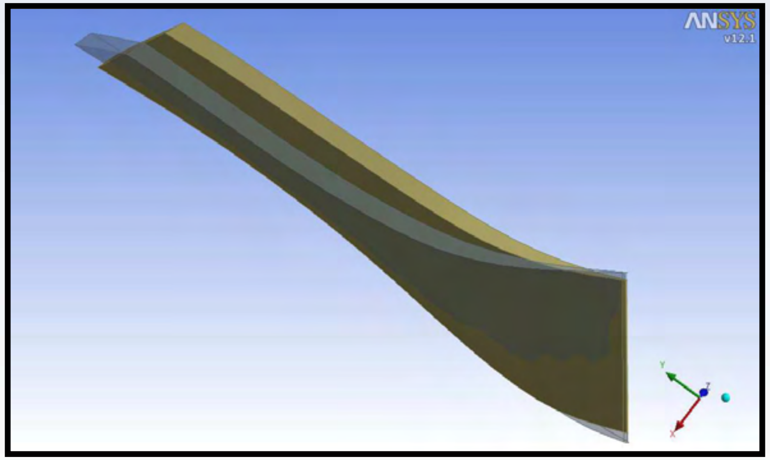


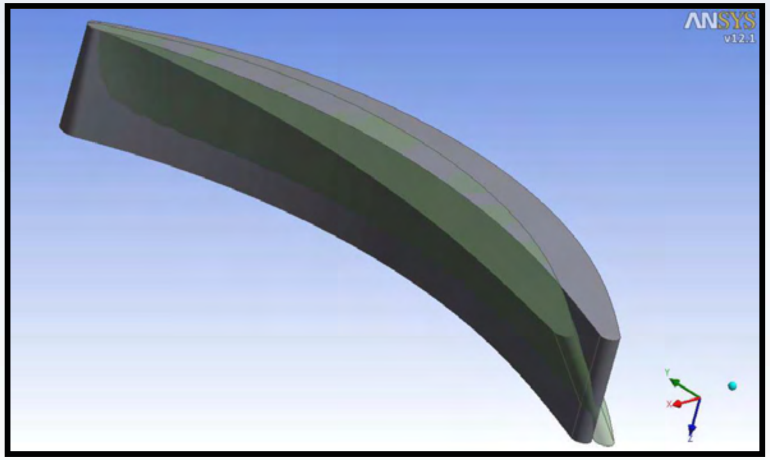


Conclusion Optimization

- Sensitivity shows better Design
- Pre-Optimization, ARSM, increases quality
- EA leads to further improvement

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



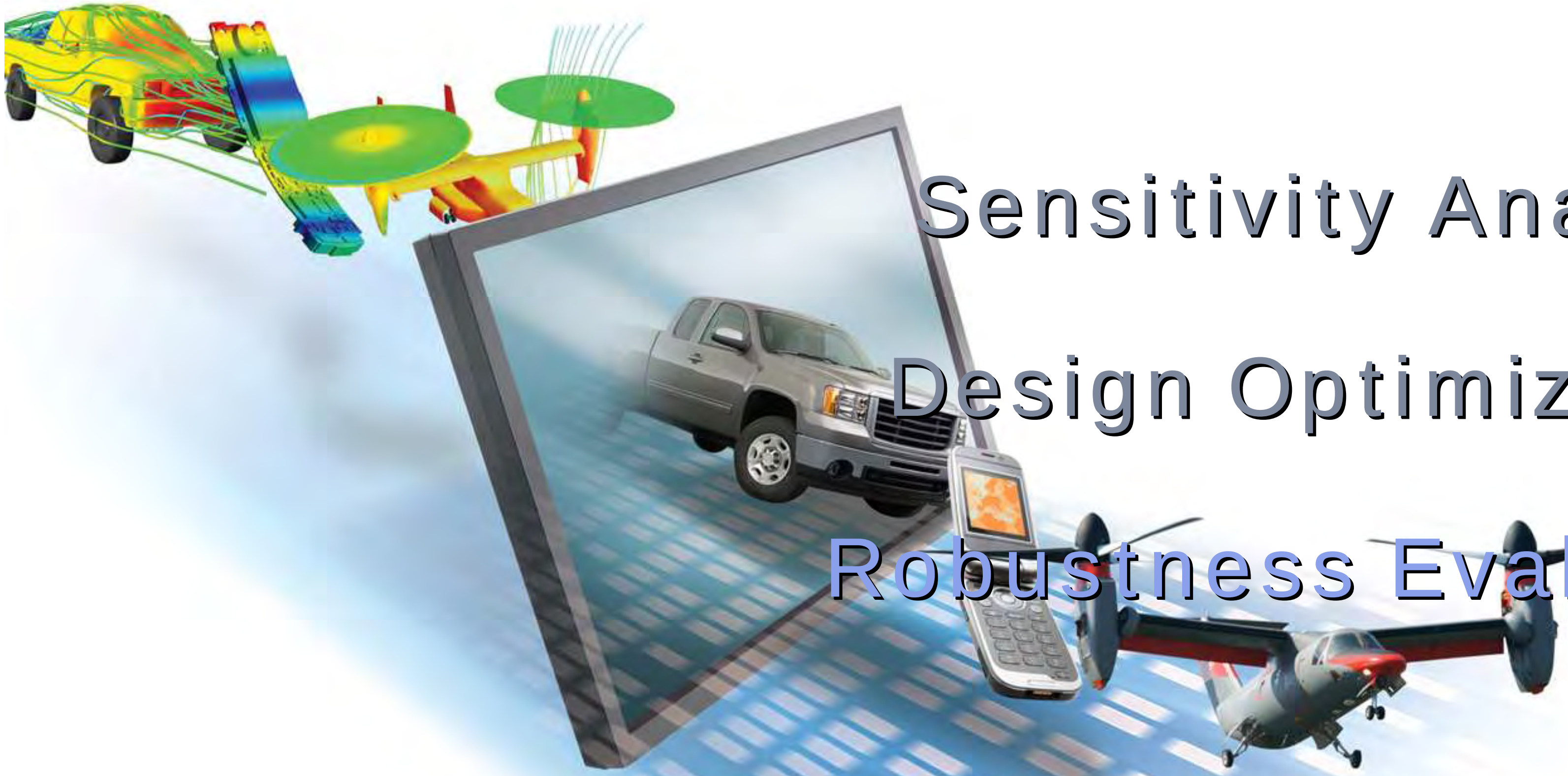


Parameterization

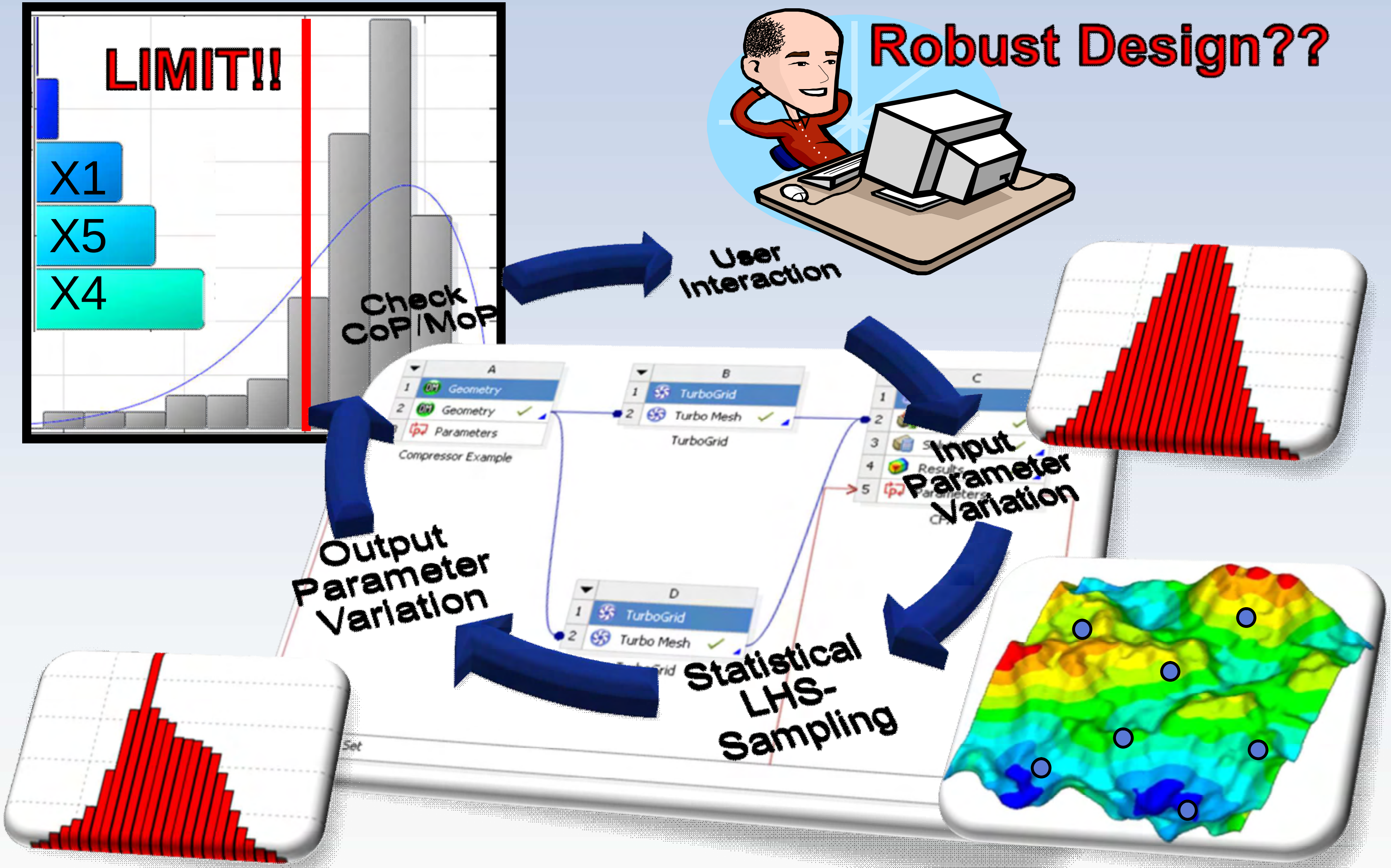
Sensitivity Analysis

Design Optimization

Robustness Evaluation

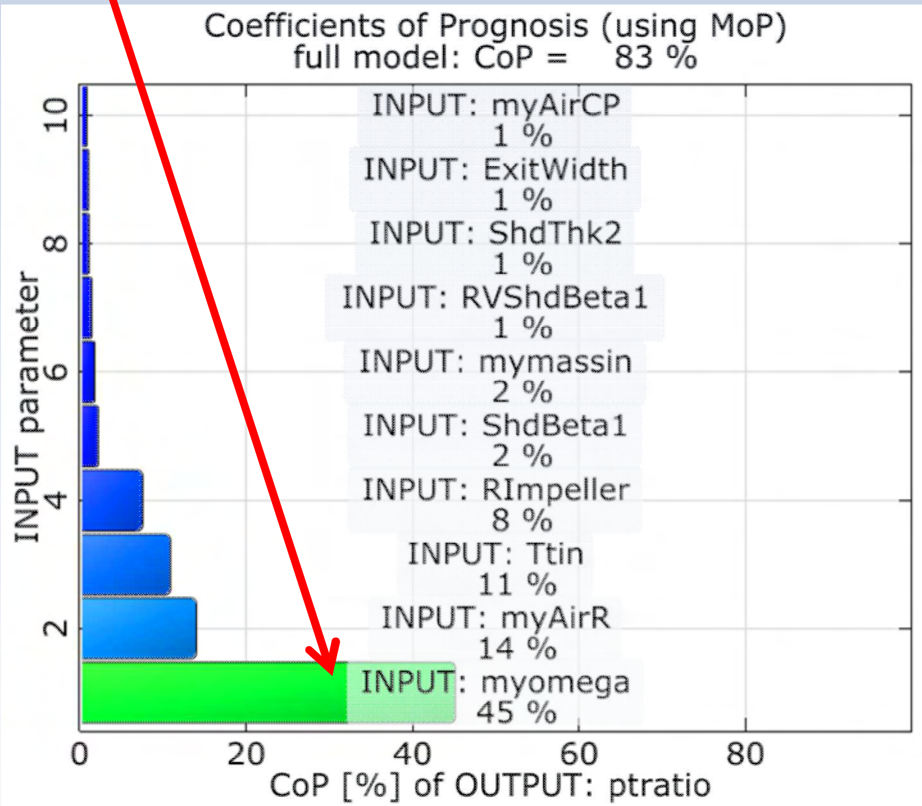


Robustness Evaluation

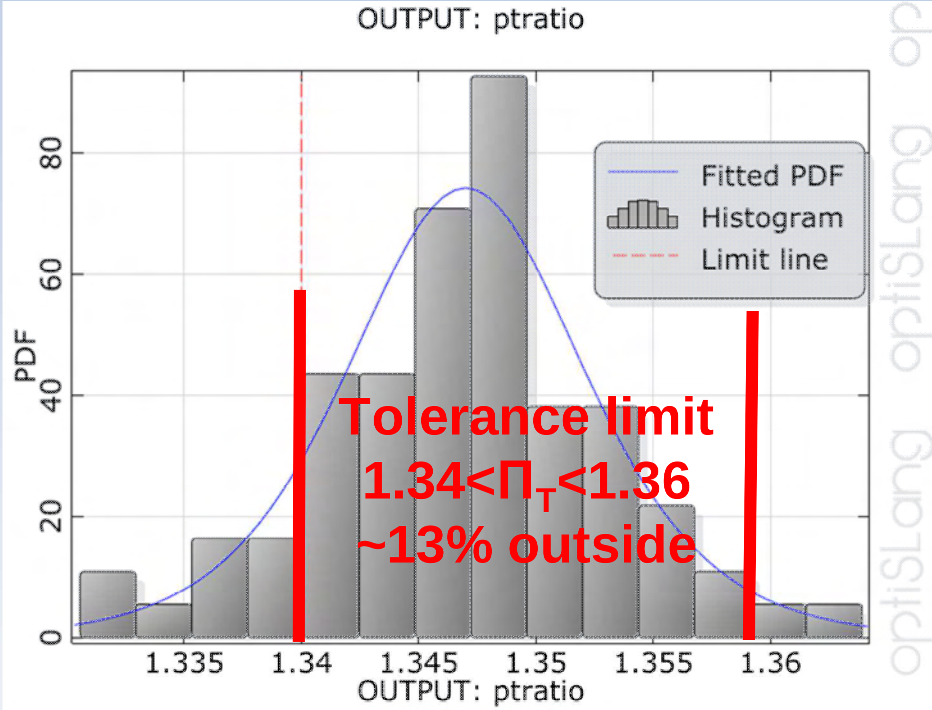


Robustness Total Pressure

Most relevant Parameter



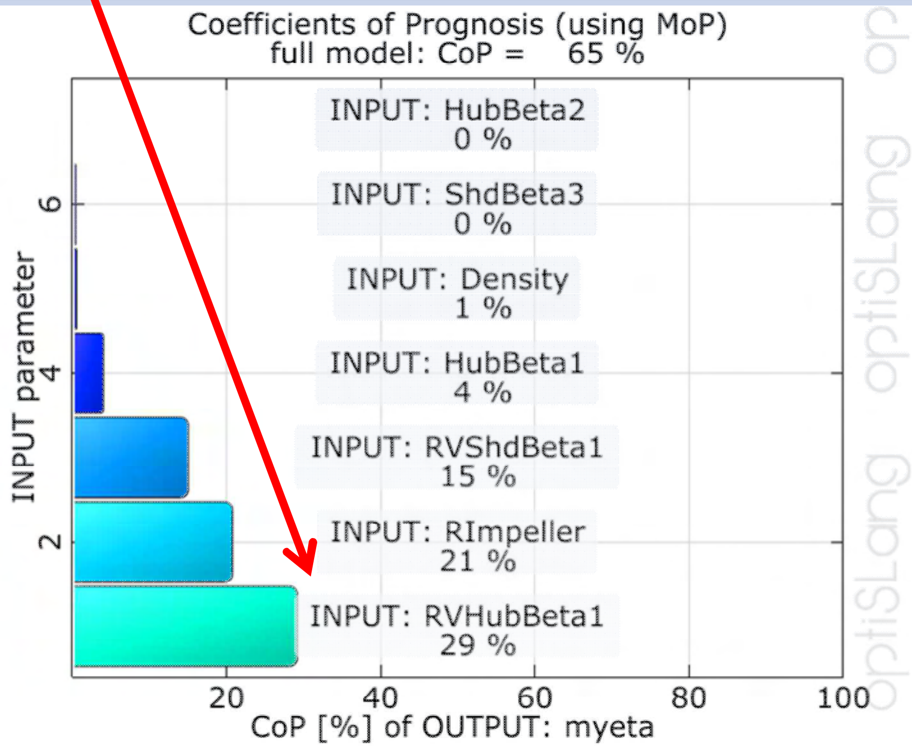
Modification of omega leads to more Robust Design



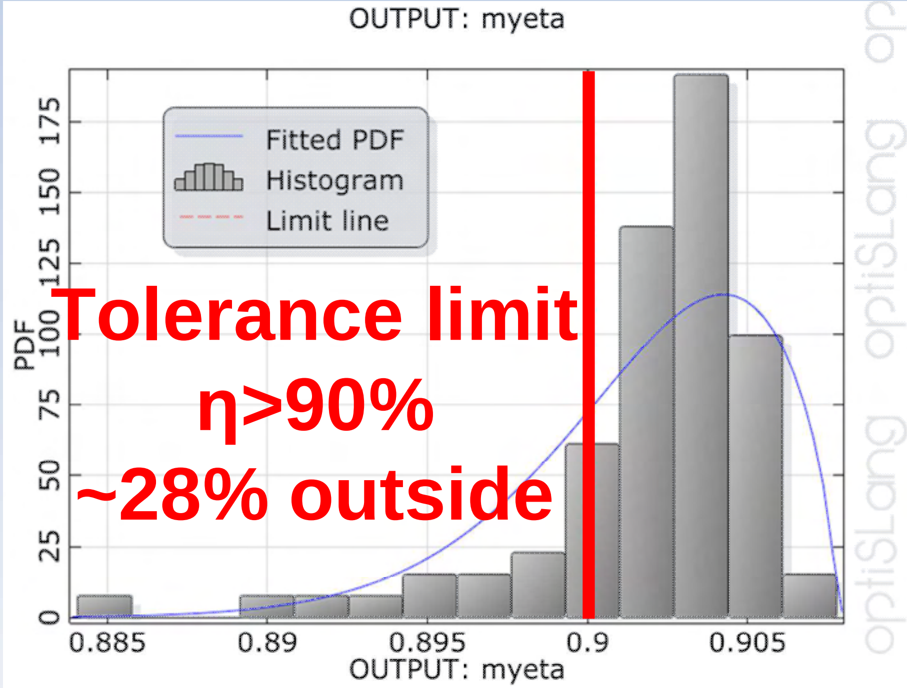
Statistic data			
Min:	1.331	Max:	1.364
Mean:	1.347	Sigma:	0.006107
CV:	0.004534		
Skewness:	-0.1683	Kurtosis:	3.589
Fitted PDF: Logistic			
Mean:	1.347	Sigma:	0.006107
Limit x = 1.34			
P_rel =	0.116883	P_fit =	0.110889

Robustness Efficiency

Most relevant Parameter

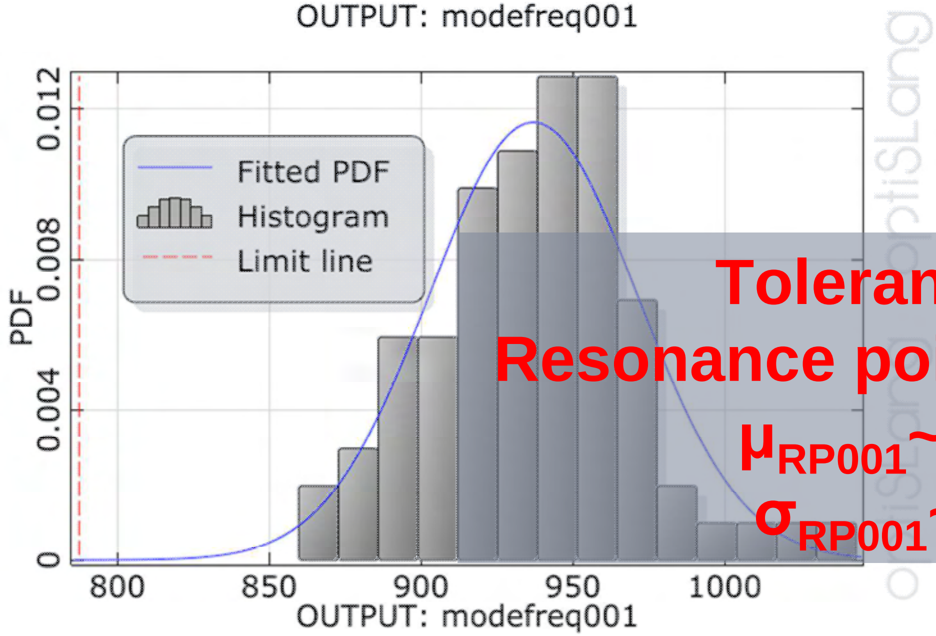


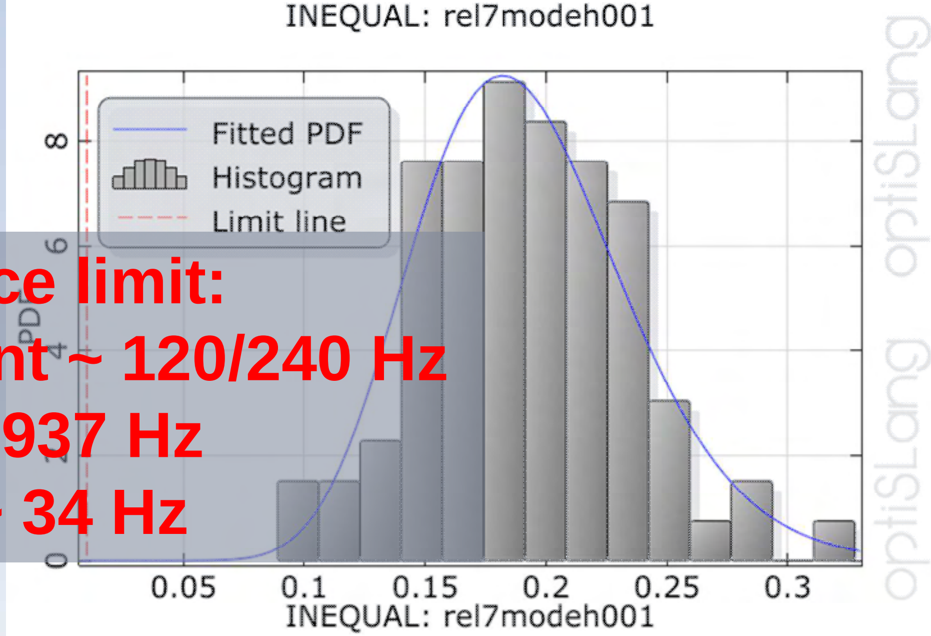
Modification of relevant parameter leads to more Robust Design



Statistic data			
Min:	0.8841	Max:	0.9078
Mean:	0.9018	Sigma:	0.003851
CV:	0.00427		
Skewness:	-2.212	Kurtosis:	9.204
Fitted PDF: Extreme Typ III (Min) Weibull			
Mean:	0.9018	Sigma:	0.003851
Upper cut:	0.9078		
Limit x = 0.9			
P_rel =	0.168831	P_fit =	0.277155

Robustness Eigen Frequency Mode 1 Harmonic Index 0





Tolerance limit:
Resonance point ~ 120/240 Hz
μ_{RP001} ~ 937 Hz
σ_{RP001} ~ 34 Hz

Statistic data			
Min:	859.7	Max:	1043
Mean:	937	Sigma:	34.25
CV:	0.03655		
Skewness:	0.315	Kurtosis:	3.467
Fitted PDF: Normal			
Mean:	937	Sigma:	34.25
Limit x = 787.4			
P_rel =	0	P_fit =	6.2614e-006

Statistic data			
Min:	0.08893	Max:	0.3278
Mean:	0.1921	Sigma:	0.0441
CV:	0.2295		
Skewness:	0.2803	Kurtosis:	3.407
Fitted PDF: Gamma			
Mean:	0.1921	Sigma:	0.0441
Limit x = 0.01			
P_rel =	0	P_fit =	2.69681e-018

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

$P(\mathcal{F}) \approx \Phi(-\beta) \approx \Phi(-0.1921 + 0.01/0.0441) = \Phi(-4.13) = 1.8 \cdot 10^{-5}$

Parameterization

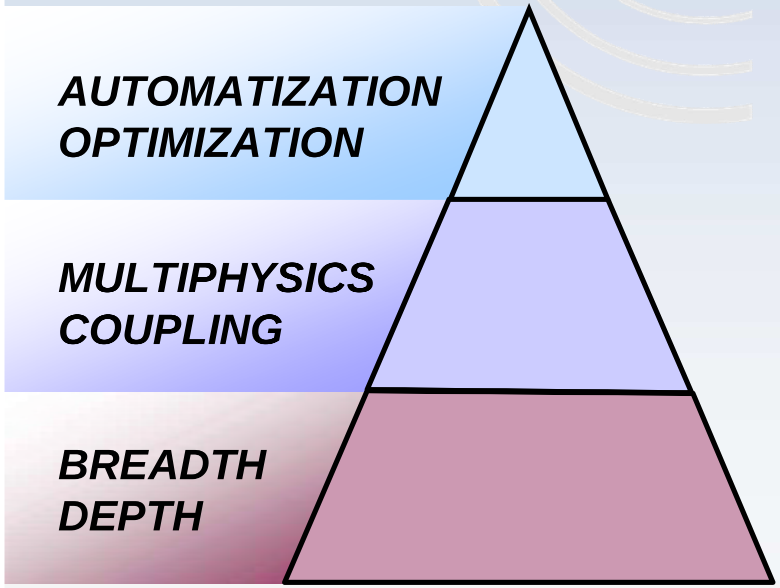
Sensitivity Analysis

Design Optimization

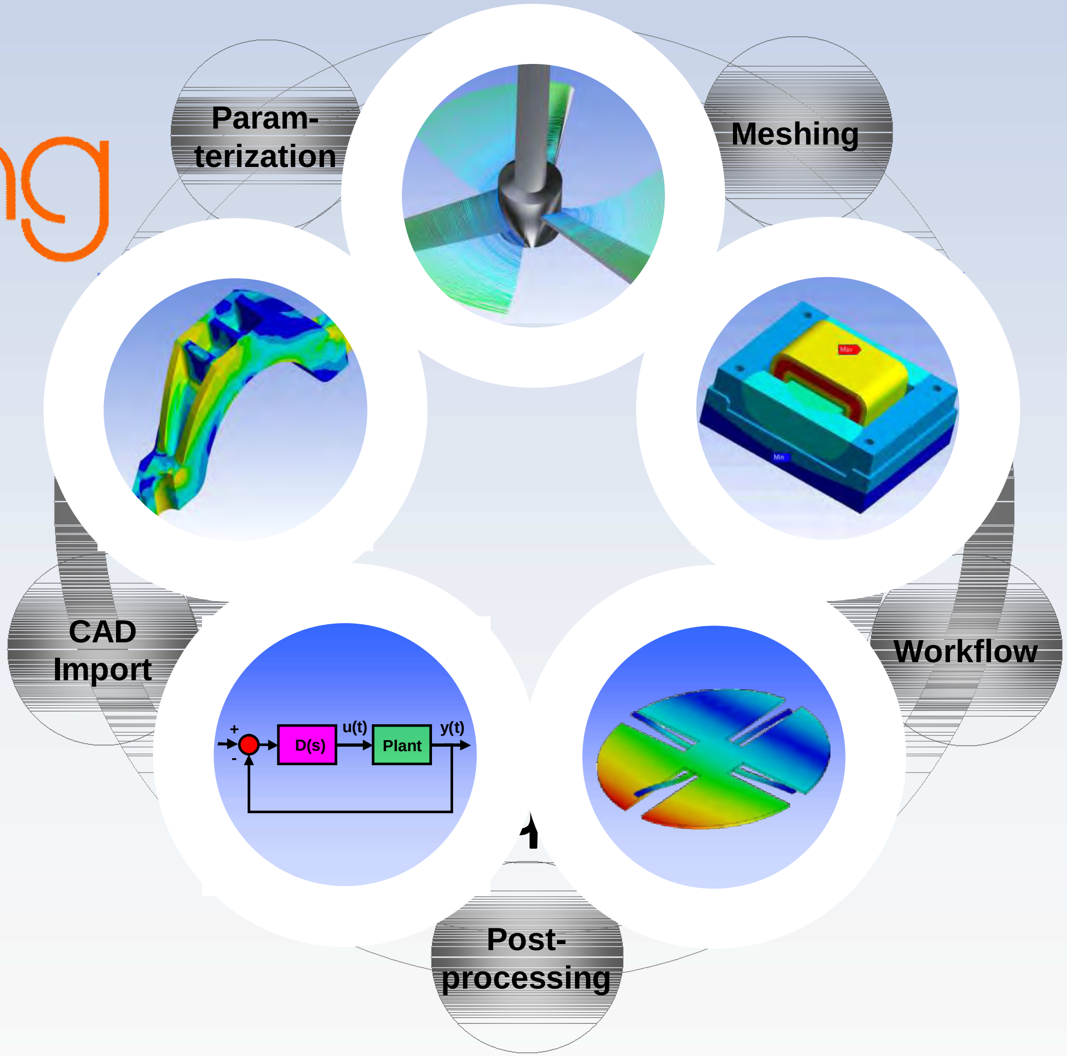
Robustness Evaluation

Summary

Summary



AUTOMATIZATION
OPTIMIZATION
MULTIPHYSICS
COUPLING
BREADTH
DEPTH



Param-
terization
Meshing
CAD
Import
Workflow
Post-
processing
D(s)
u(t)
Plant
y(t)

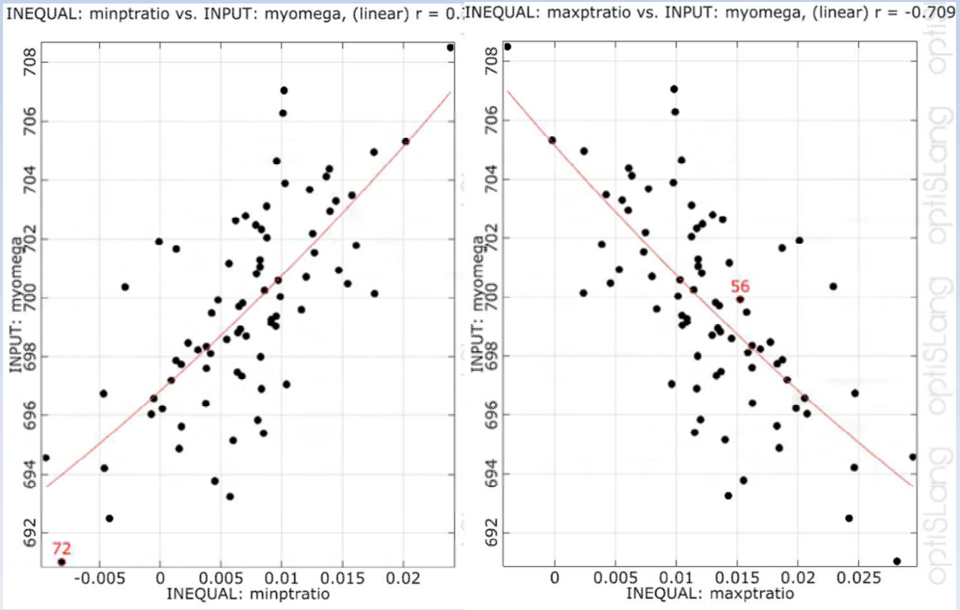
Robust Design Optimization of a Centrifugal Compressor Part II

Dirk Roos
DYNARDO GmbH
dirk.roos@dynardo.de

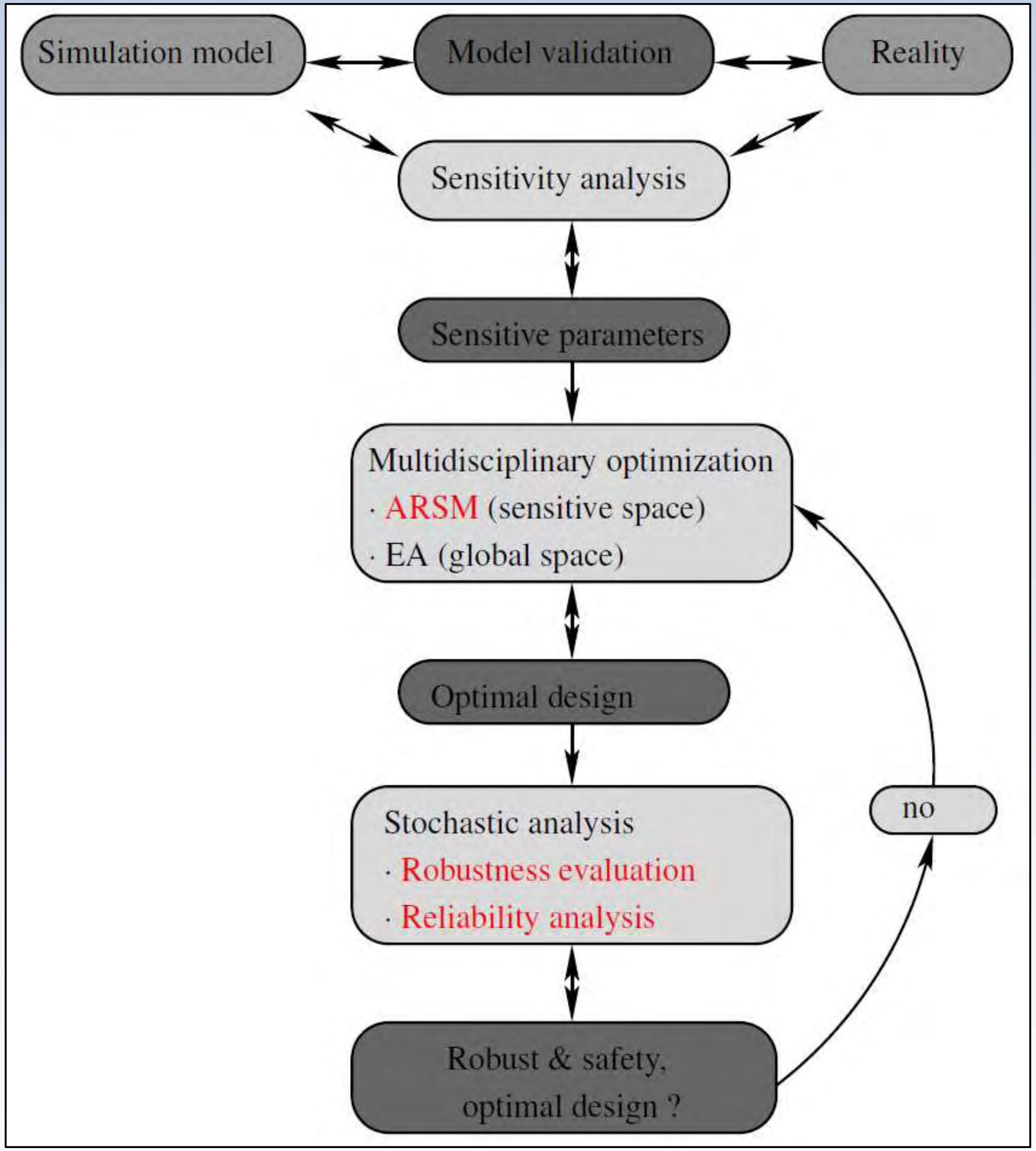
Johannes Einzinger
ANSYS Continental Europe
johannes.einzinger@ansys.com

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

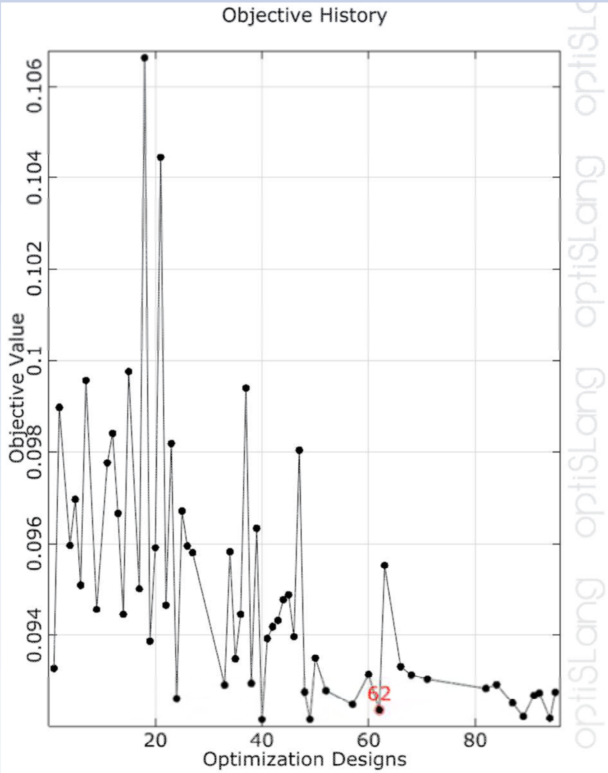
Design Optimization II

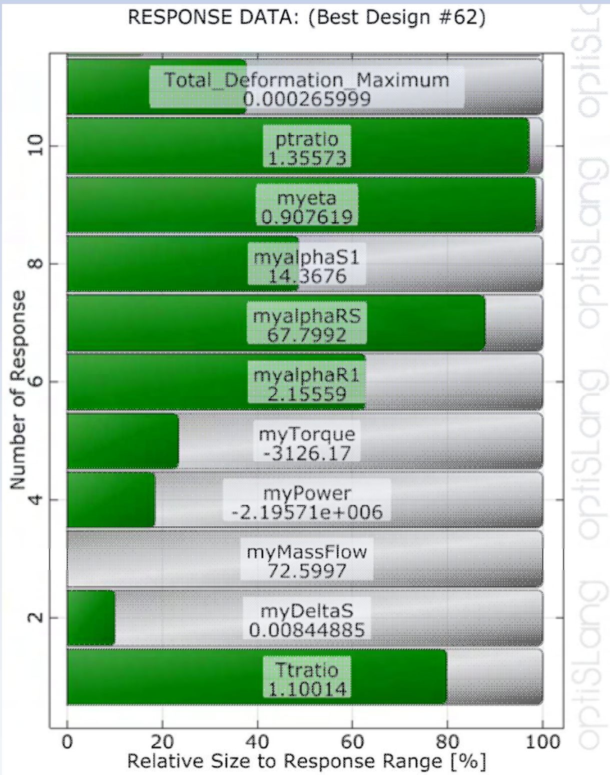
Opti | Robust | Output | Strings | Constraints | Objectives

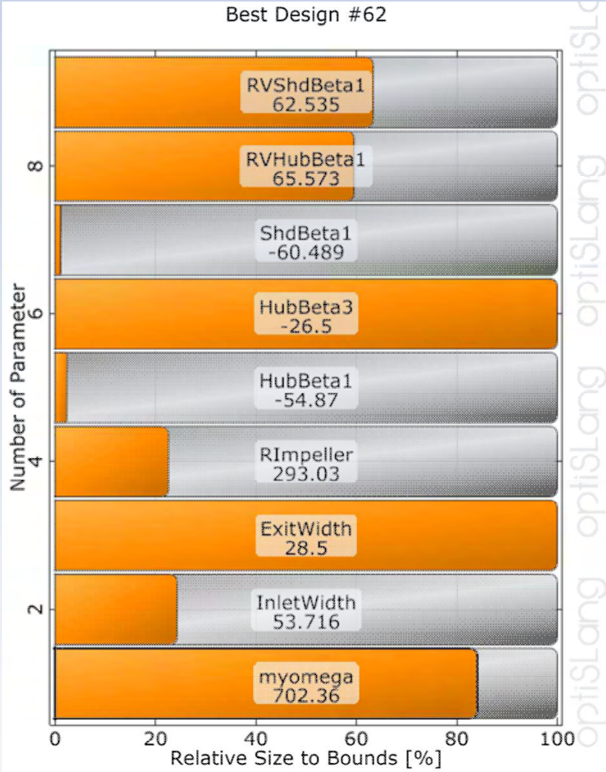
#	Name	Value	Ref.Value	Lower Bound	Upper Bound	Type	Format	Active	Const...
1	myomega	699.76	699.76	699.0	703.0	continuous	%20.14f	[x]	[ ]
2	InletWidth	53	53.6136610657...	52.5	57.5	continuous	%20.14f	[x]	[ ]
3	ExitWidth	26	27.8049298398...	26.5	28.5	continuous	%20.14f	[x]	[ ]
4	RImpeller	305	292.556879245...	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

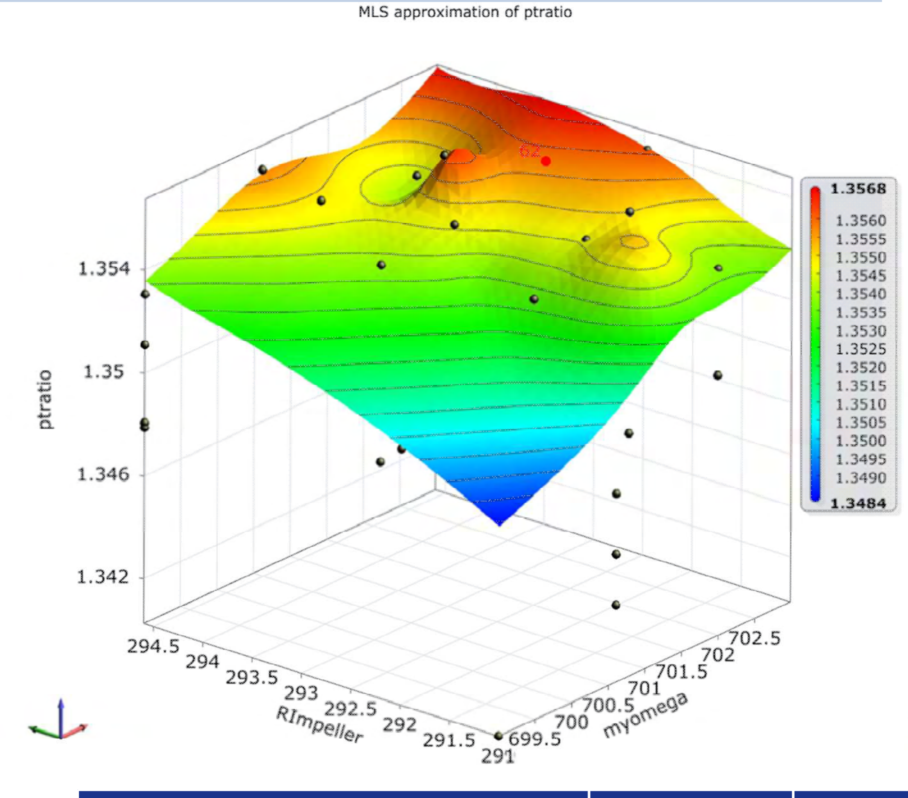
Design Optimization II: ARSM

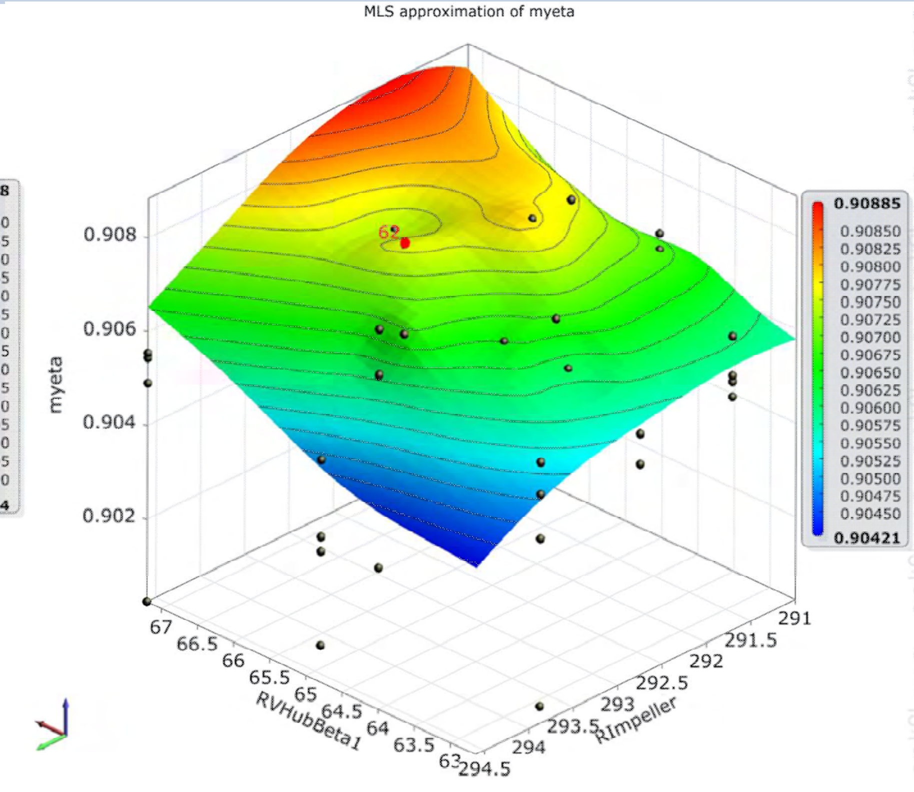






Design Optimization II: ARSM





	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**

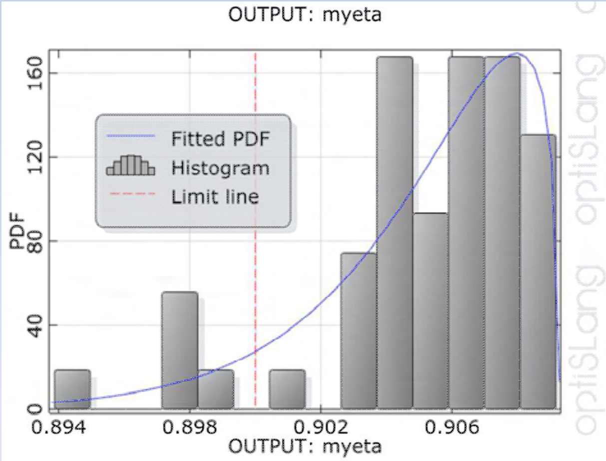
Design Optimization II

Robustness Evaluation II

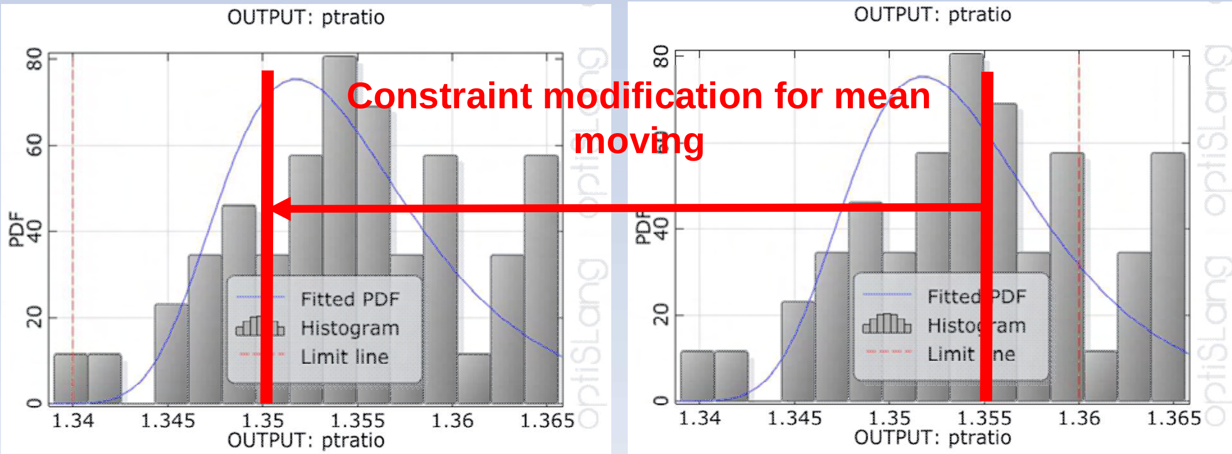
Robust Design Optimization

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

Tolerance limit η<90%
~8% outside

Tolerance limit
Π_T>1.36
~17% outside

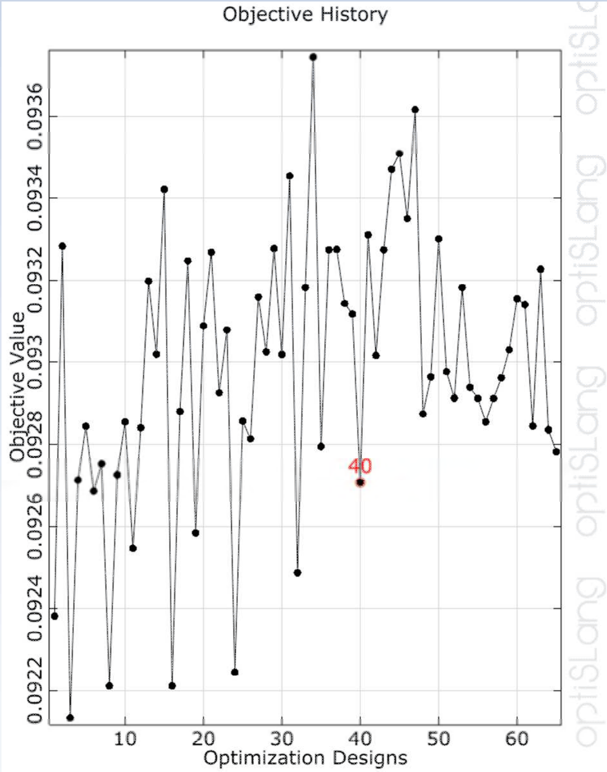
Design Optimization III

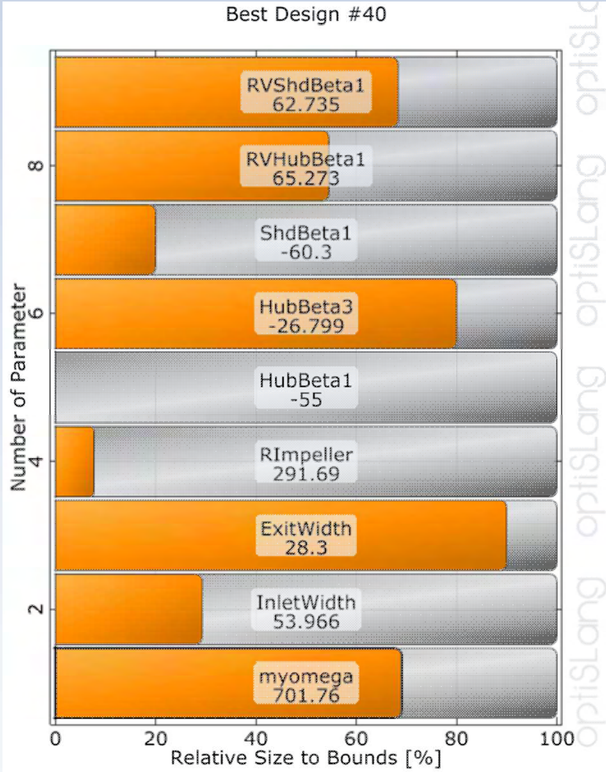
Robustness Evaluation III

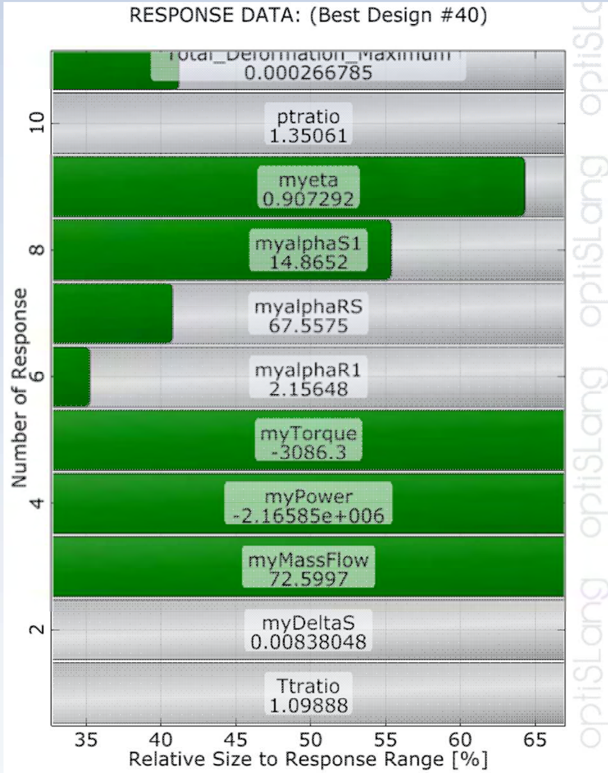
Robust Design Optimization

Reliability Analysis

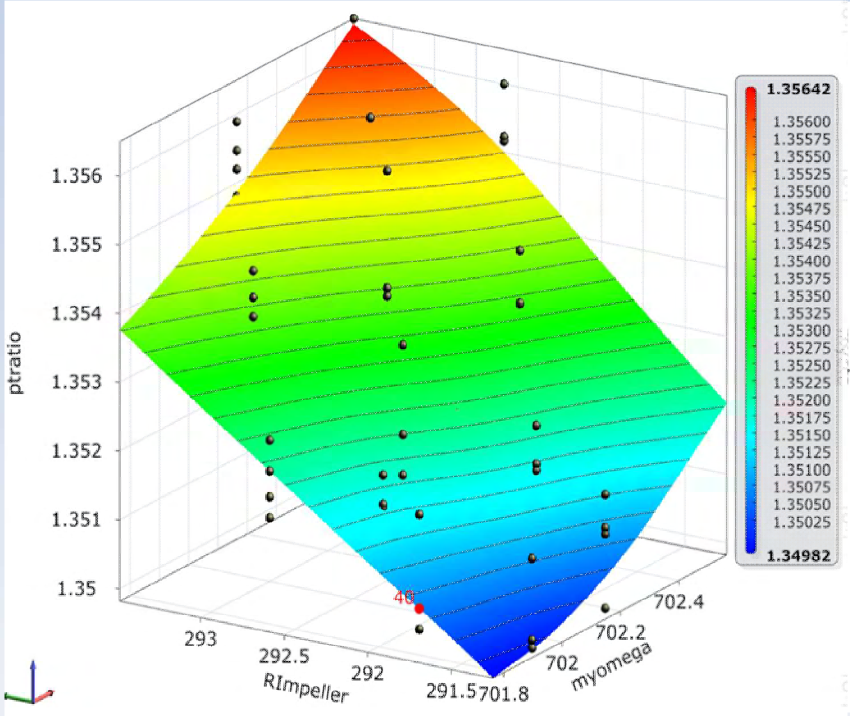
Design Optimization III: ARSM

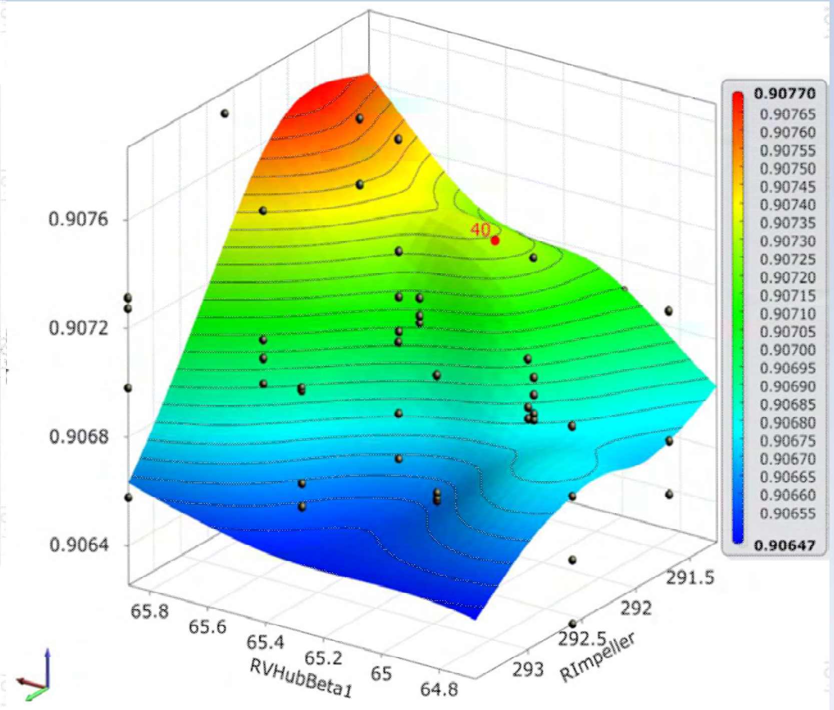






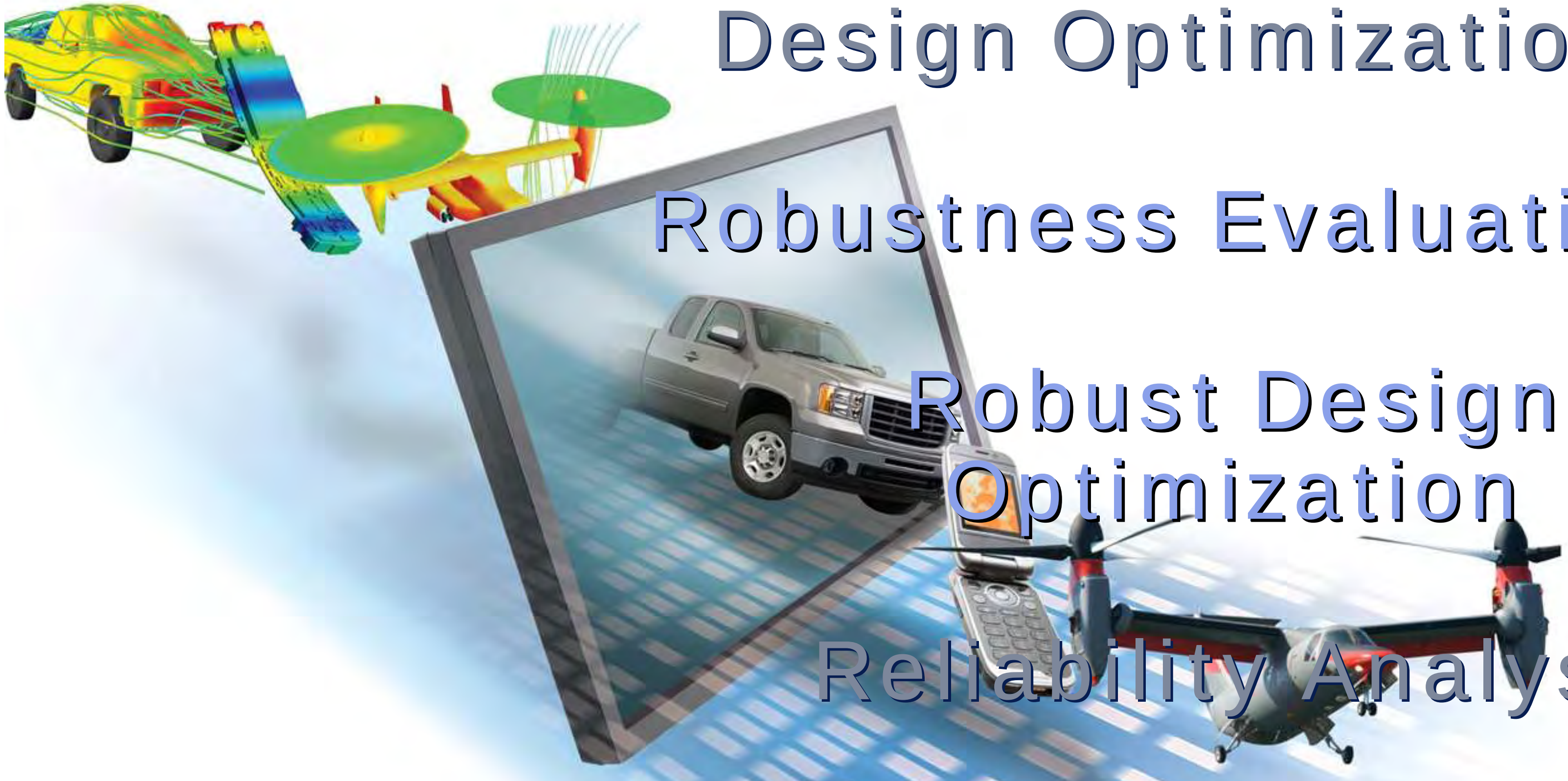
Design Optimization III: ARSM





	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

ANSYS
dynardo



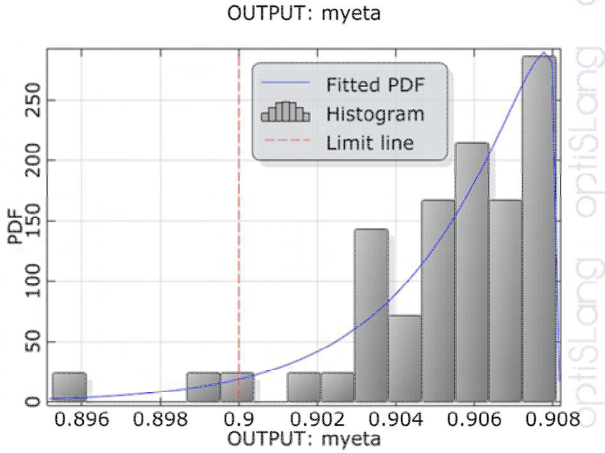
Design Optimization III

Robustness Evaluation III

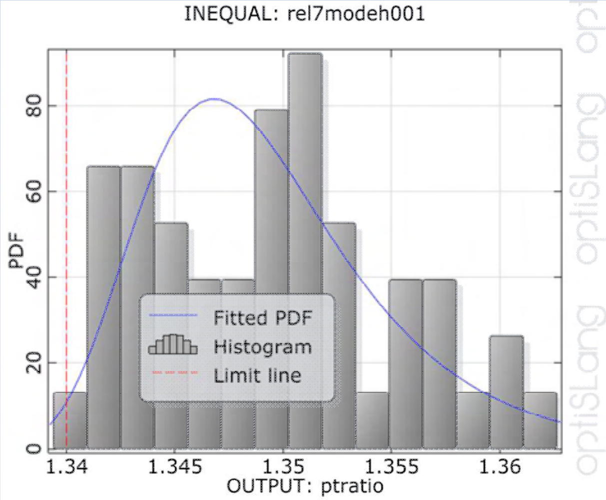
Robust Design Optimization

Reliability Analysis

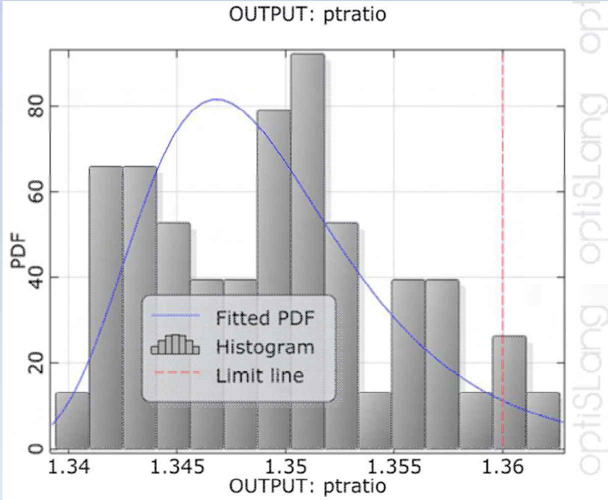
Robust evaluation III: LHS



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



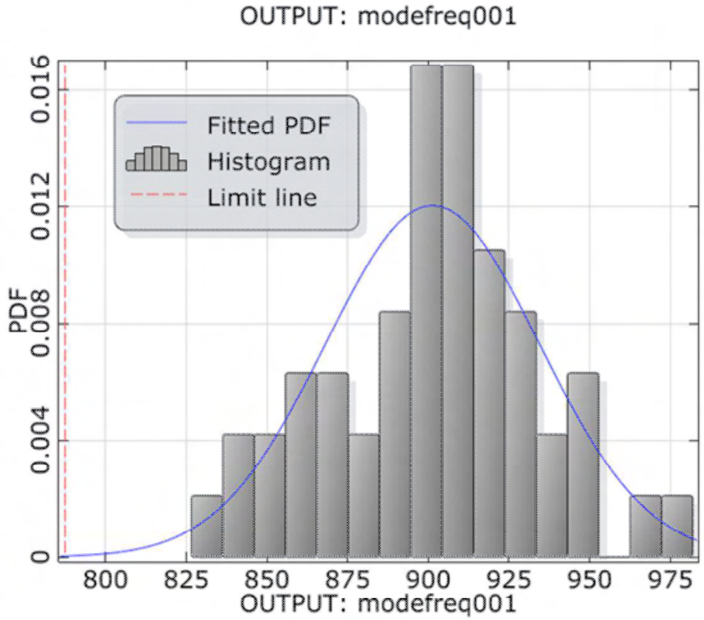
Statistic data			
Min:	1.339	Max:	1.363
Mean:	1.349	Sigma:	0.005782
CV:	0.004285		
Skewness:	0.3347	Kurtosis:	2.38
Fitted PDF: Fisher-Tippett			
Mean:	1.349	Sigma:	0.005782
Limit x = 1.36			
P_rel =	0.938776	P_fit =	0.947814

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

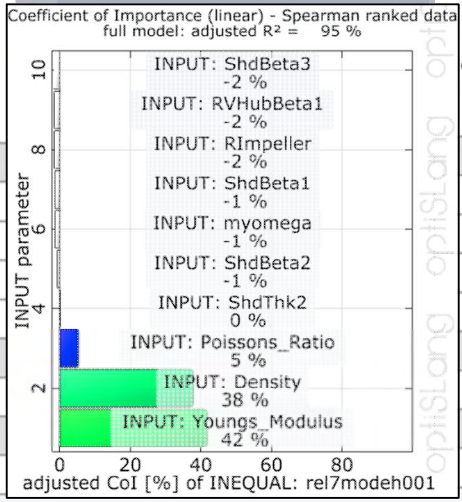


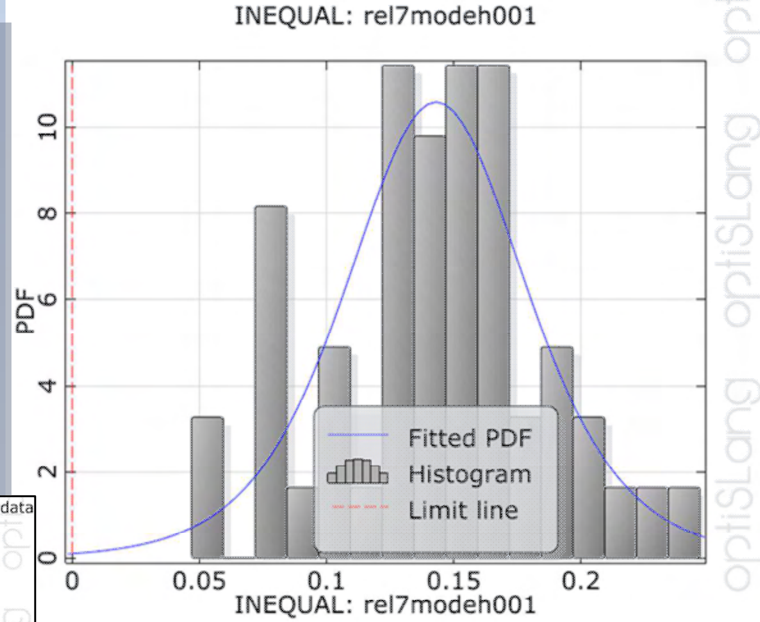
Statistic data			
Min:	826.6	Max:	982
Mean:	901.3	Sigma:	33.18
CV:	0.03682		
Skewness:	-0.04593	Kurtosis:	2.862
Fitted PDF: Normal			
Mean:	901.3	Sigma:	33.18
Limit x = 787.4			
P_rel =	0	P_fit =	0.000299089

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?

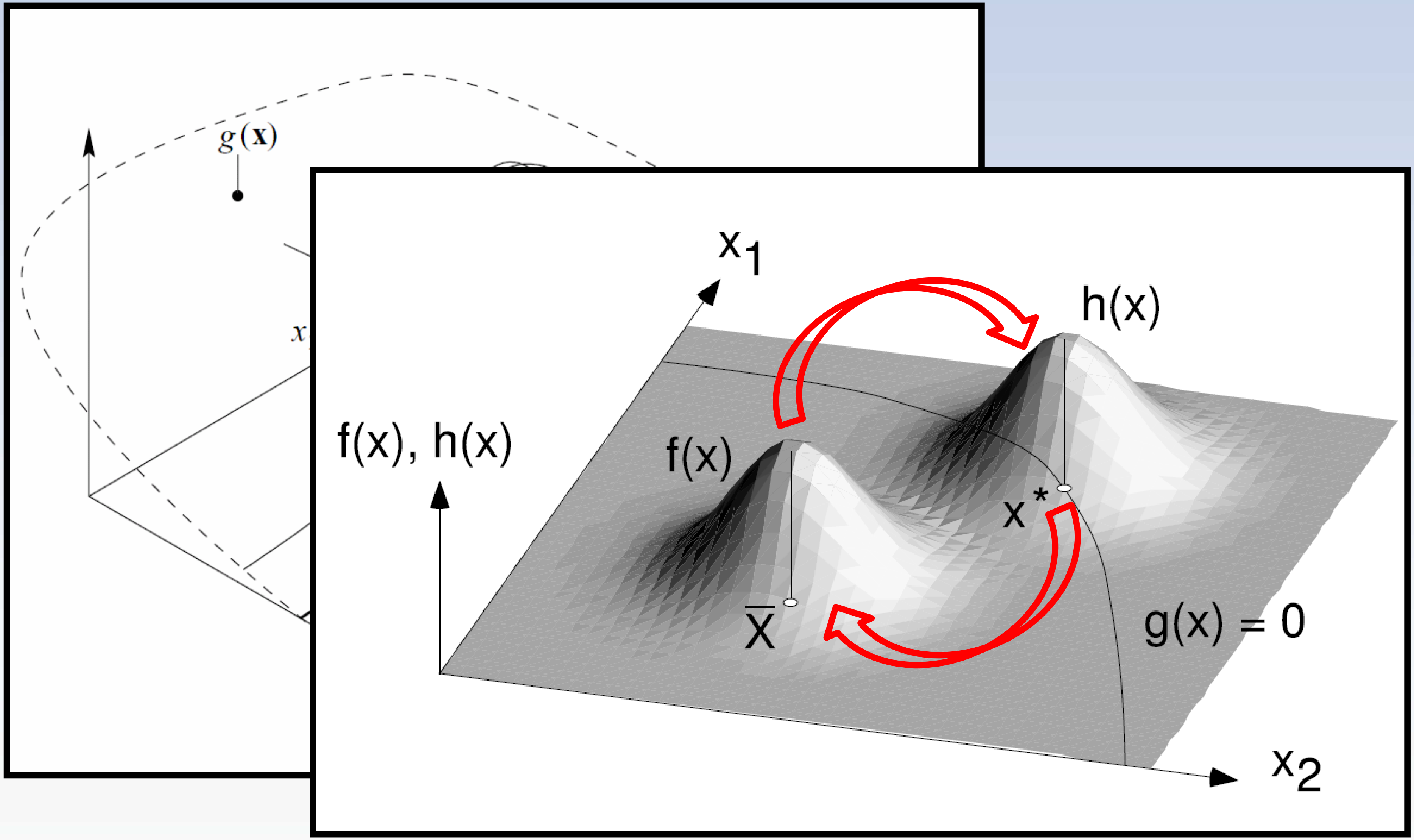
Design Optimization

Robustness Evaluation

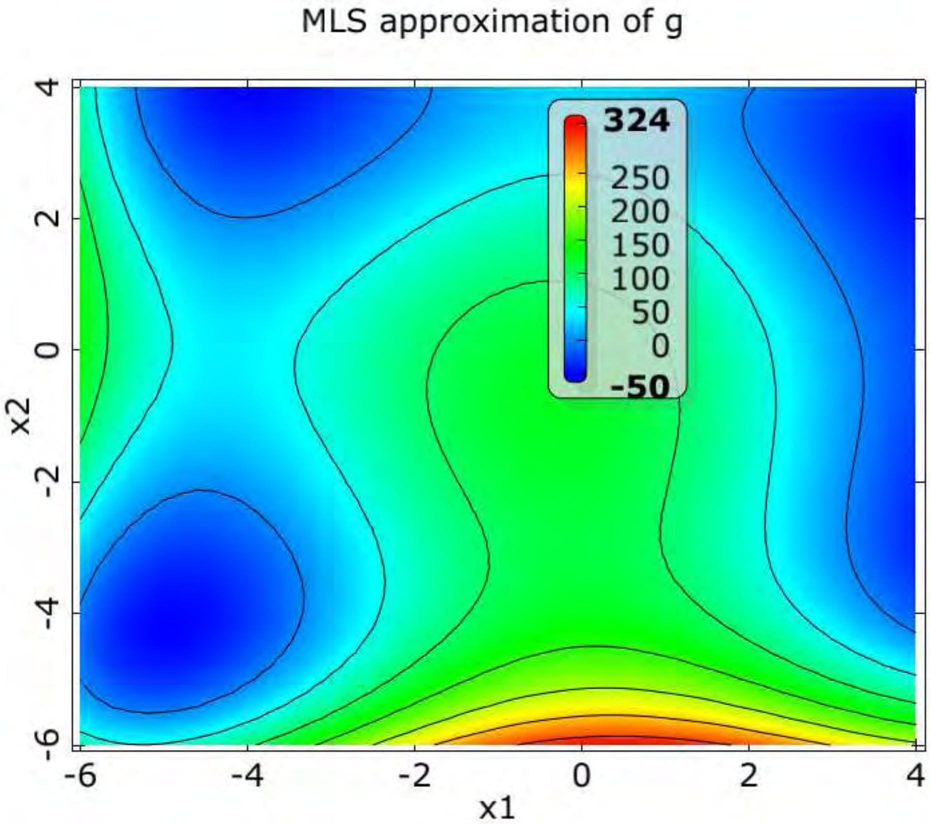
Robust Design Optimization

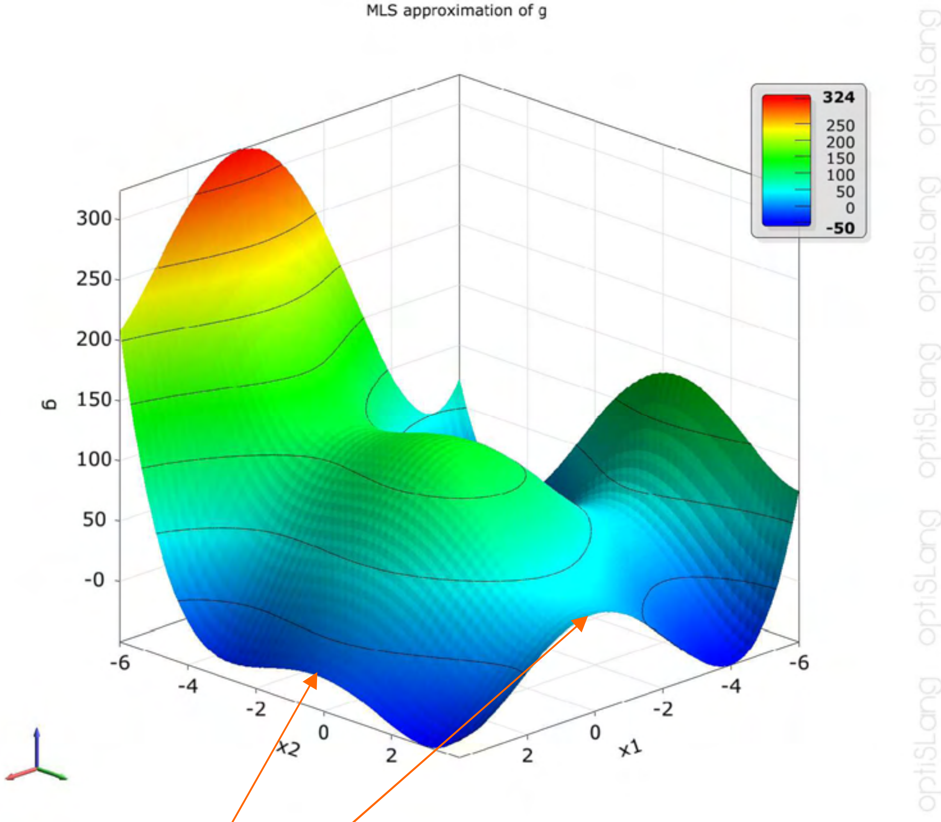
Reliability Analysis

Reliability Analysis



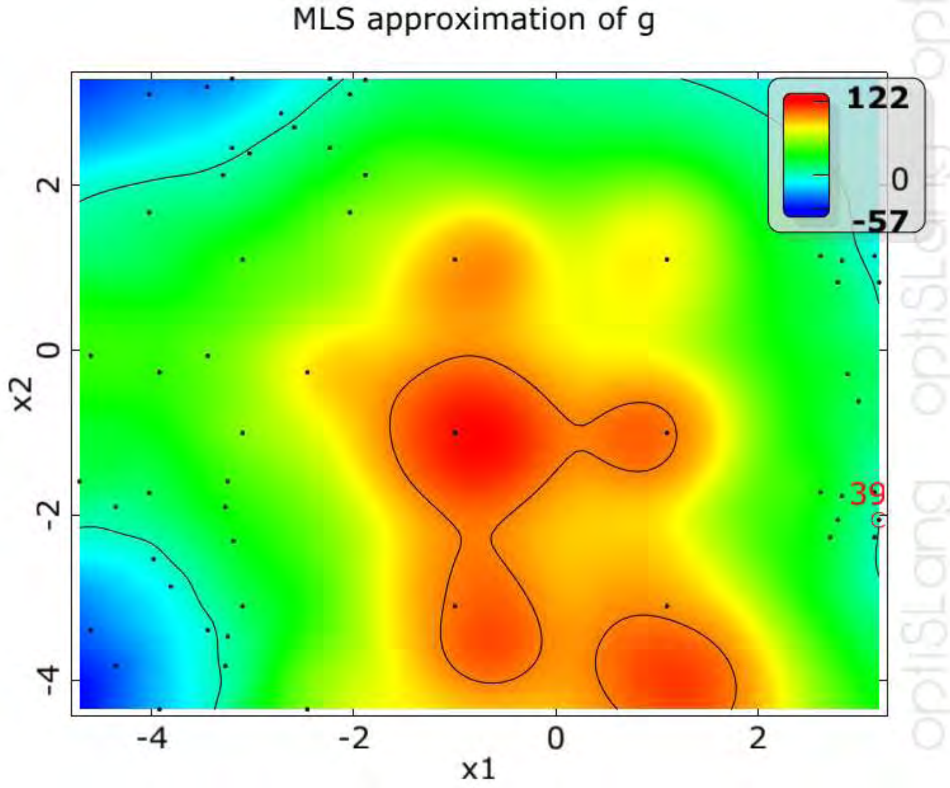
Reliability Analysis

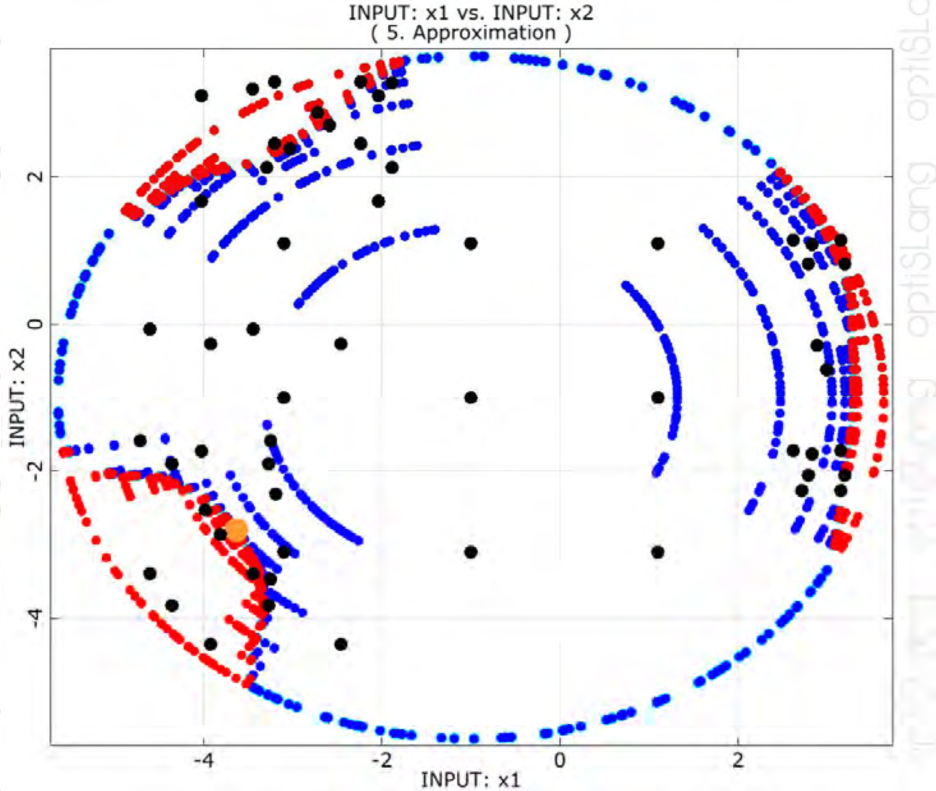




- Himmelblau function
- Nonlinear two dimensional state function g(x1,x2)
- Nonlinear limit state function g(x1,x2)=0
- Three separated domains with high failure probability density

Reliability Analysis

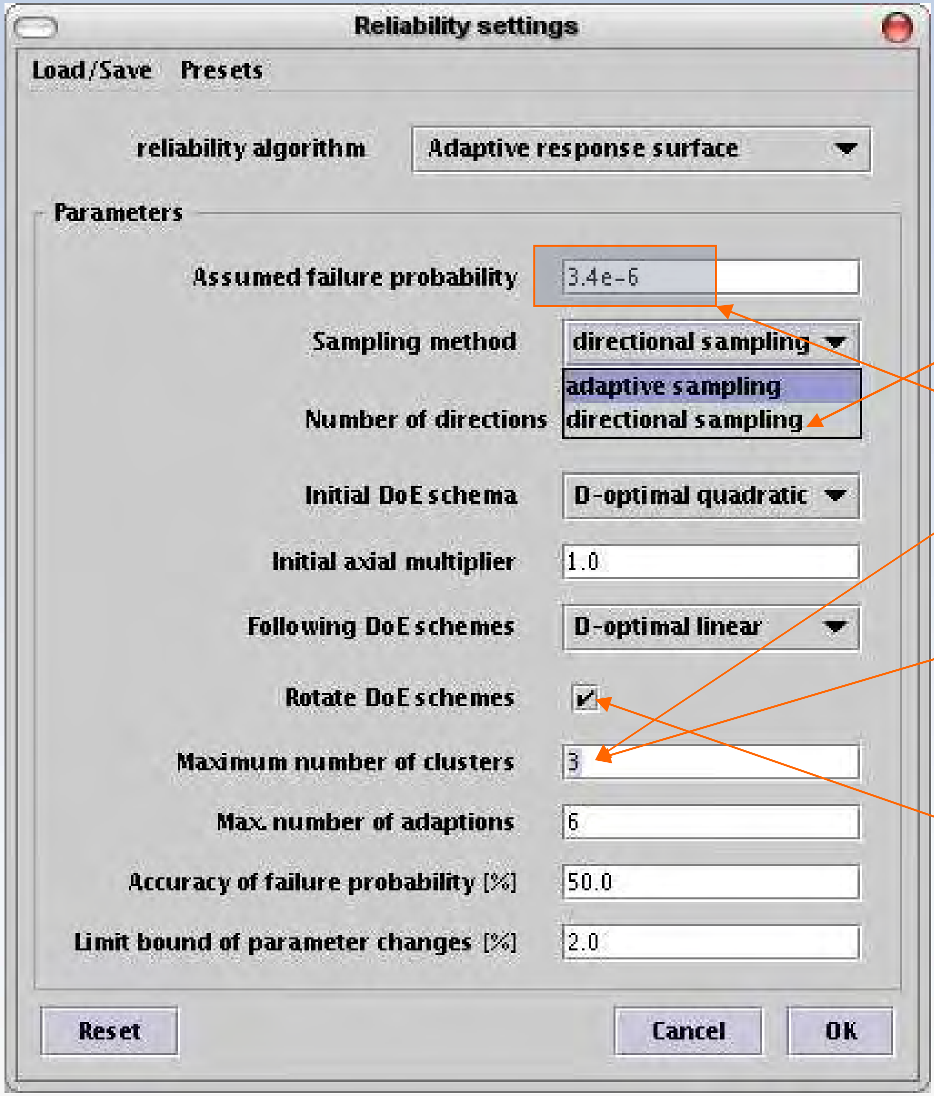




- Adaptive response surface method
- Directional sampling on MLS
- Design evaluations: 58
- PF = 1.67E-06 (1.99E-06)

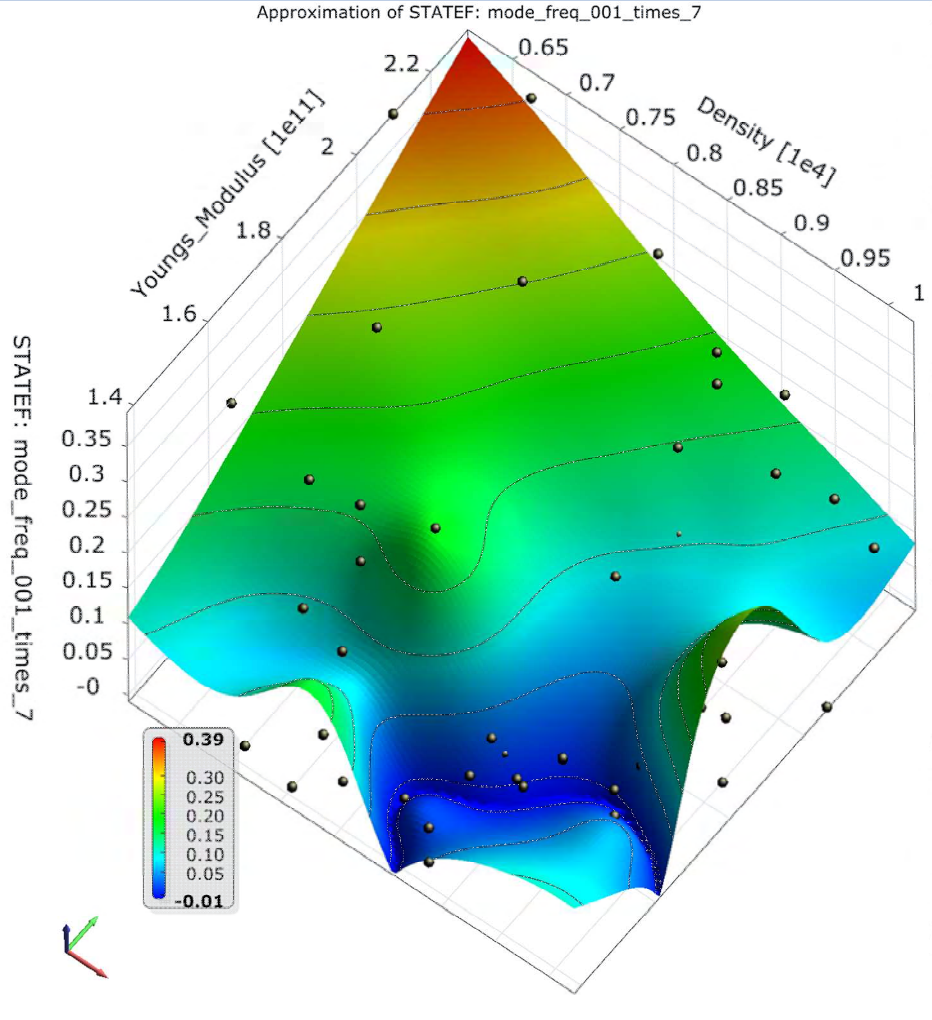
- Sigma level independent
- n ≤ 20
- Multiple adaptive DOE
- Supports multi-domain limit states

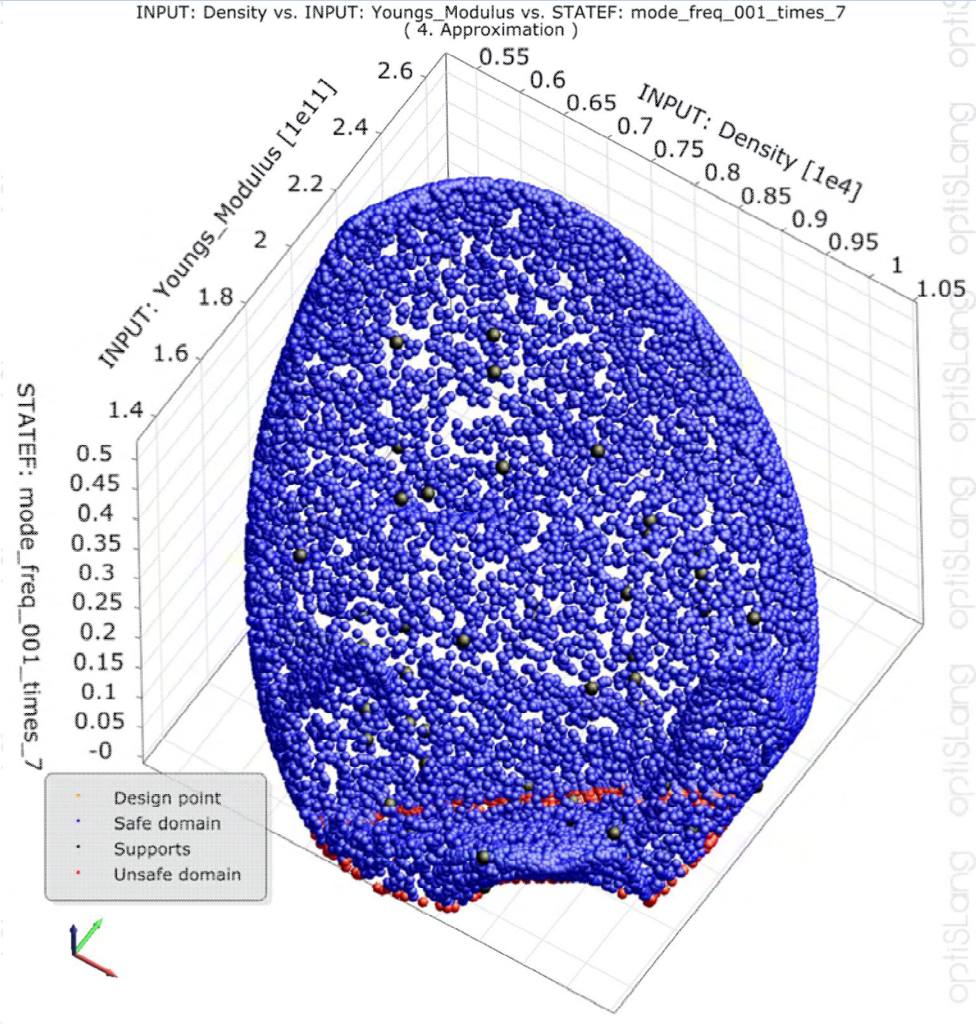
Adaptive response surface approximation



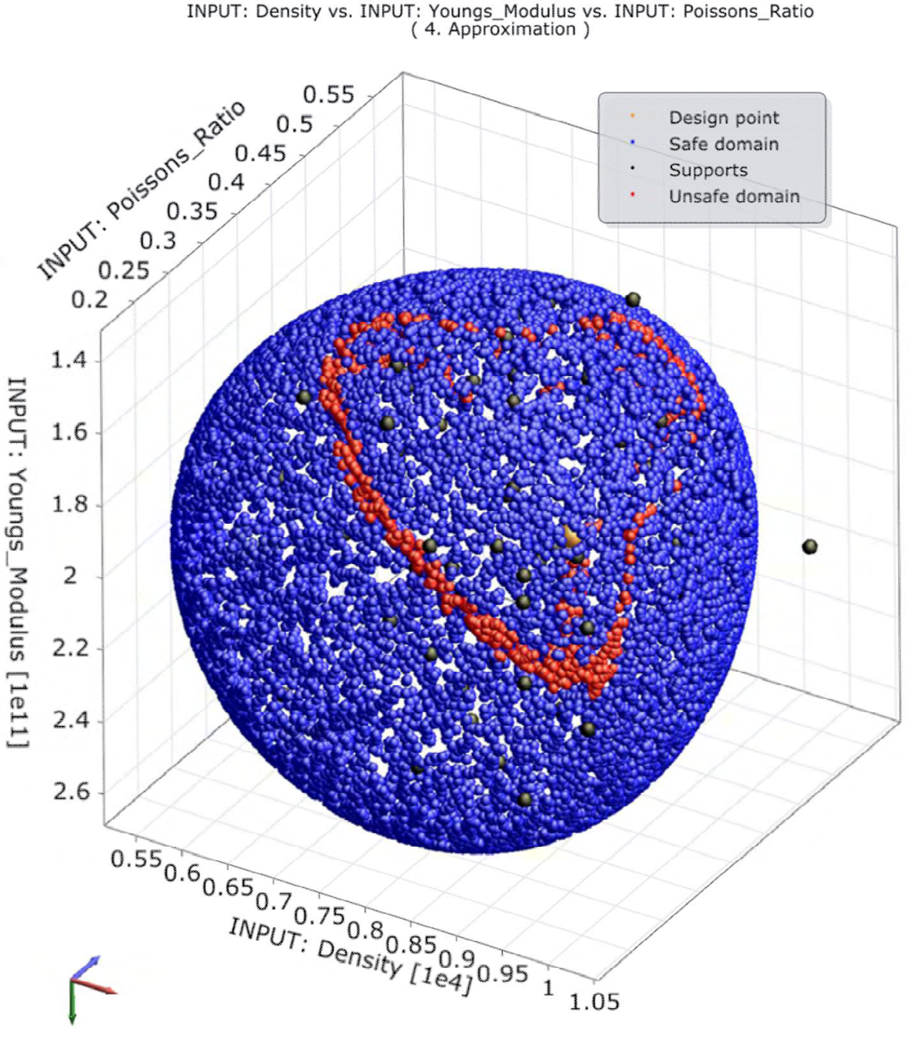
- Sampling methods on the MLS approximation:
  - Adaptive Sampling
  - Directional Sampling
    - supports more than two failure domains
    - and sigma level independent
- Cluster analysis to detect number of failure domains with high failure probability
- Rotatable adaptive designs of experiments to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

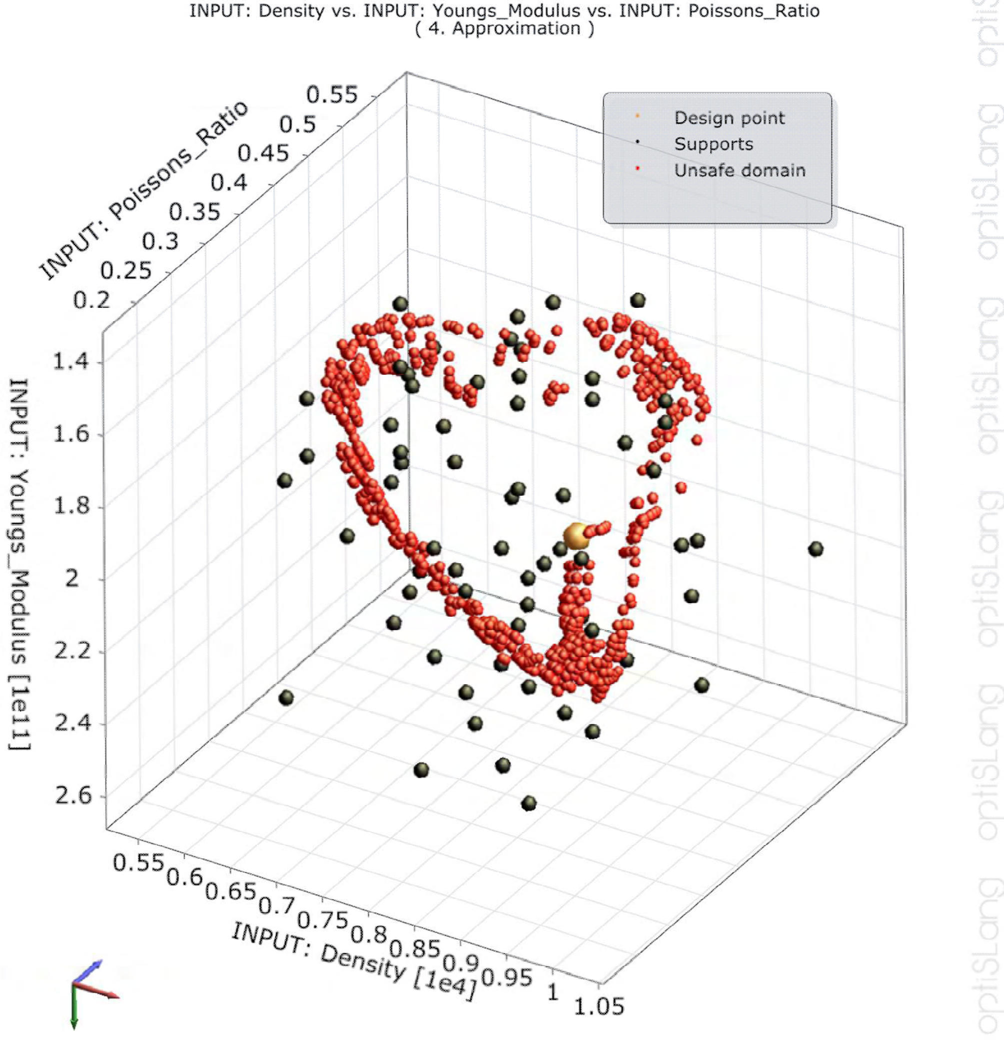
Reliability Analysis



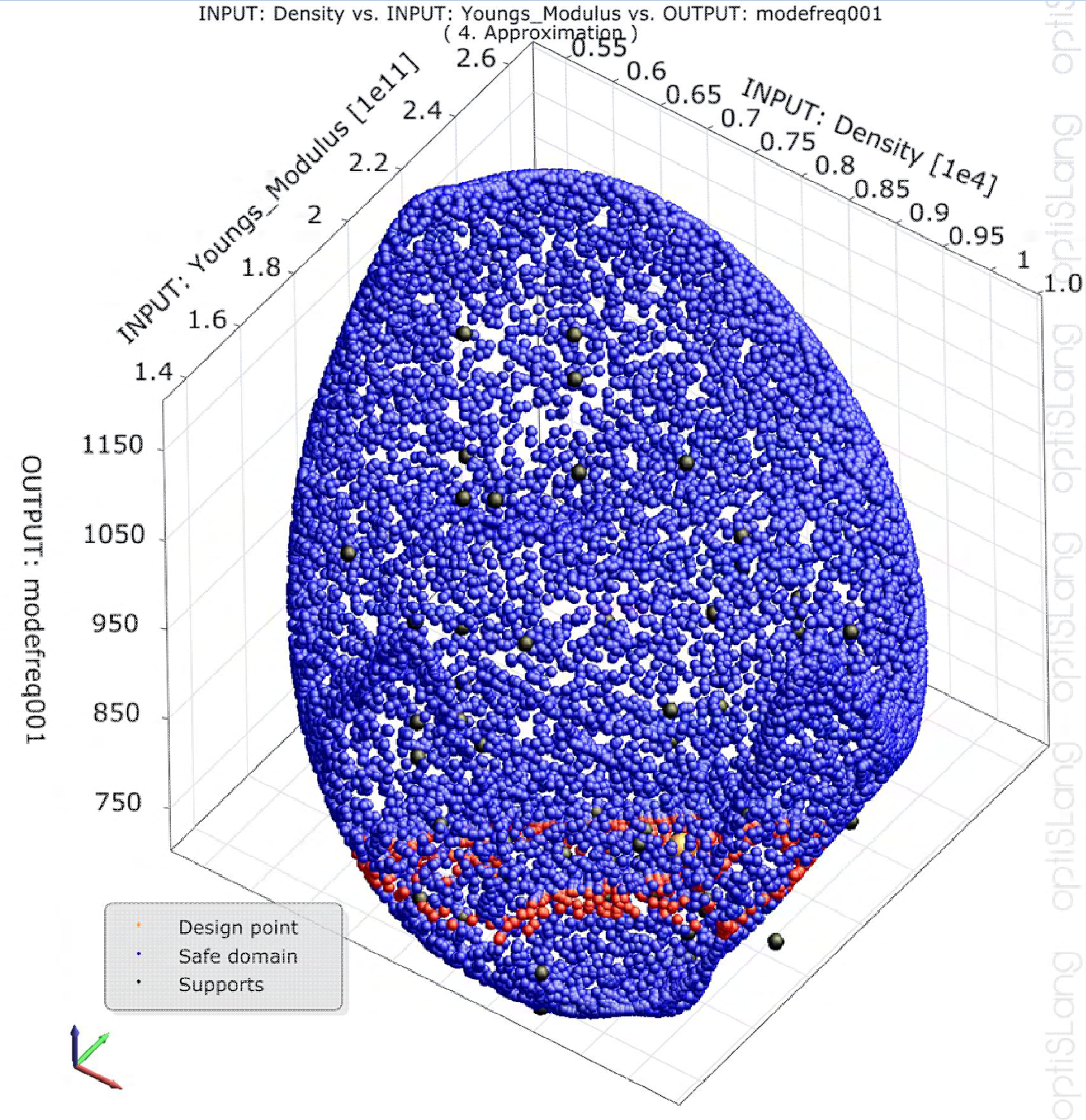


Reliability Analysis





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:

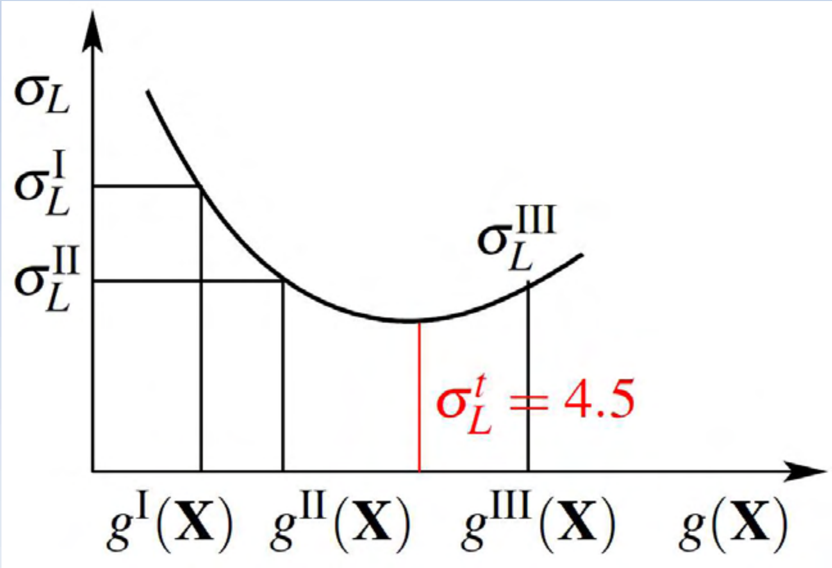
Density :9279.86887124
Youngs_Modulus :177034428177
Poissons_Ratio :0.285958415968

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)