Fluid-Structure Simulation of an Axial Turbine using ANSYS Workbench and Robust Design Optimization with Manufacturing Tolerances using optiSLang

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Outline

- **Process integration**
  - Parameterization of the Process and Geometry
- **Sensitivity Analysis**
  - Multivariate statistic
  - Meta-modeling
- **Design Optimization**
  - Evolutionary Algorithm
  - Adaptive Response Surface Method
- **Robustness Evaluation**
  - Random Variables
  - Random Fields
- **Design for Six Sigma**
  - Reliability Analysis
  - Robust Design Optimization

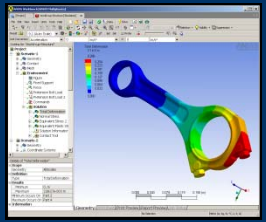
Workbench Platform & optiSLang

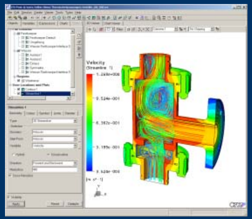
ANSYS

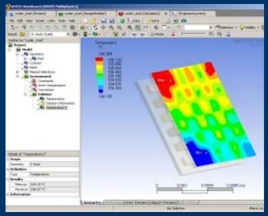
CATIA SolidWorks UGS The PLM Company **CAD / PDM** PTC autodesk

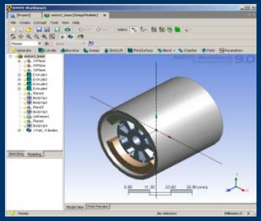
ANSYS Workbench

Structural Mechanics - Fluid Dynamics - Heat Transfer - Electromagnetics









An adaptable multi-physics design and analysis system that integrates and coordinates different simulation tasks

Sensitivity | **Robustness** | **Optimization** | **Reliability** | **Robust Design**

optiSLang

Parameterization
Process & Geometry

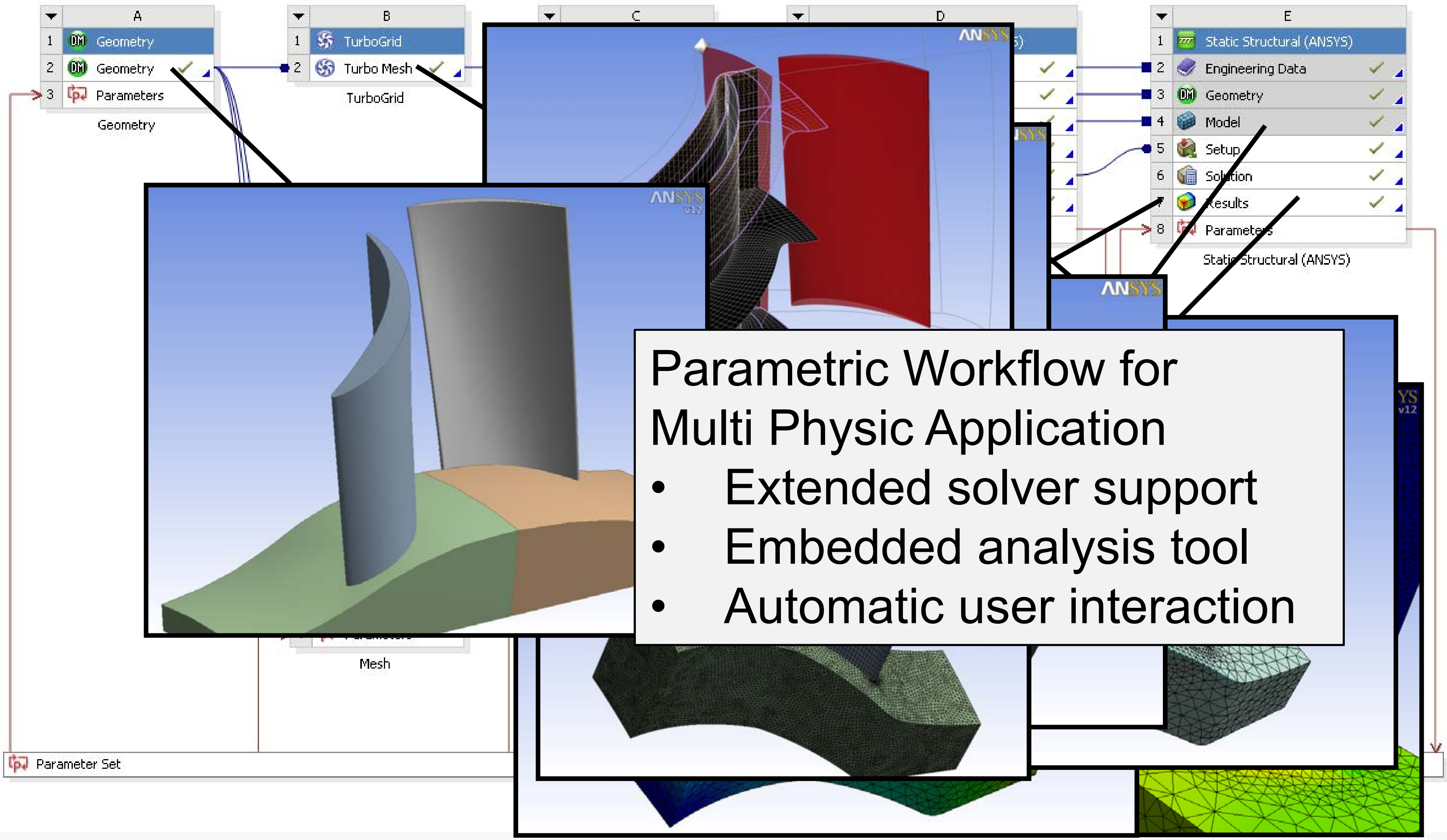
Sensitivity Analysis

Design Optimization

Robustness Evaluation

Design for Six Sigma

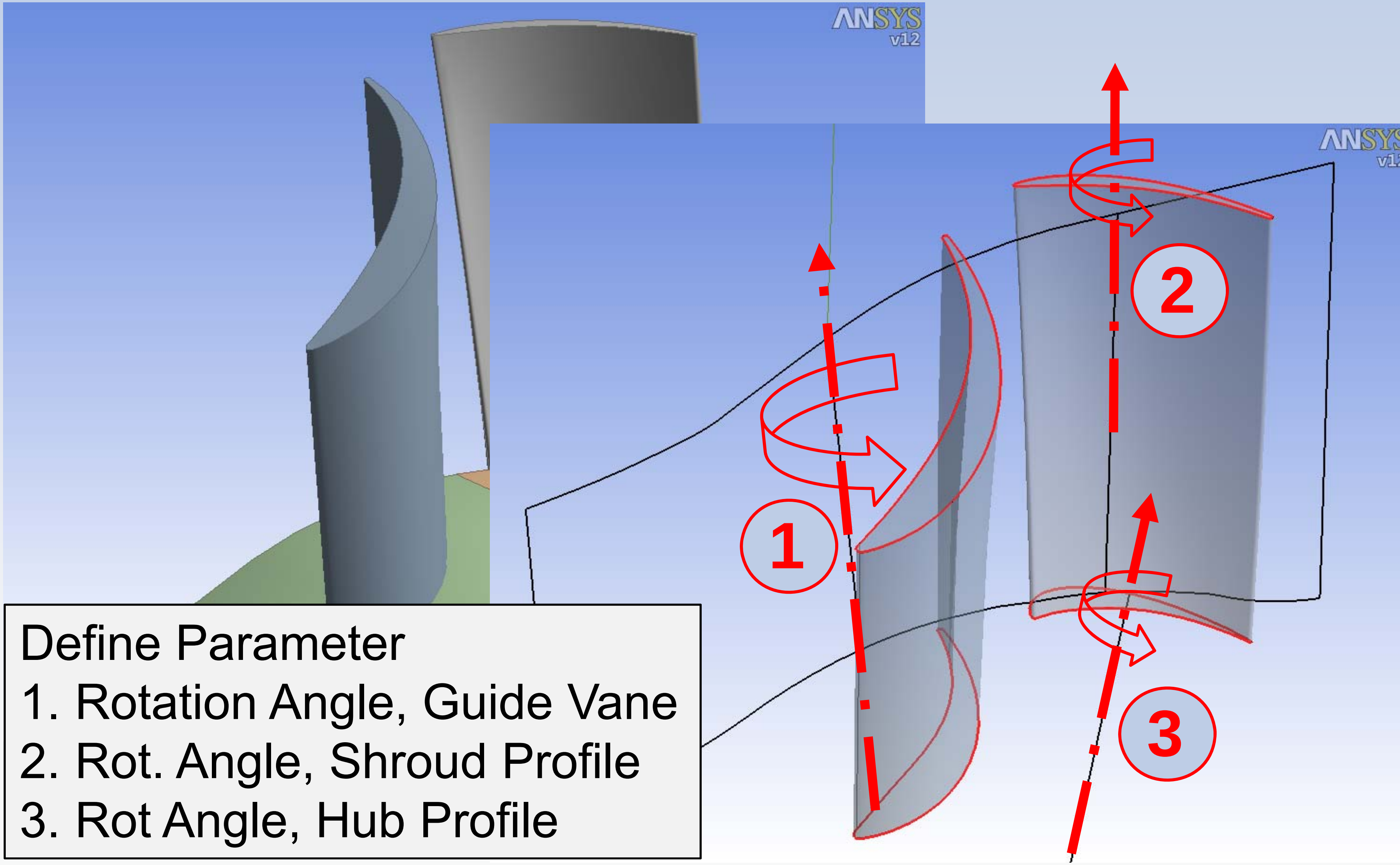
Parameterization of the Workflow



Parametric Workflow for Multi Physic Application

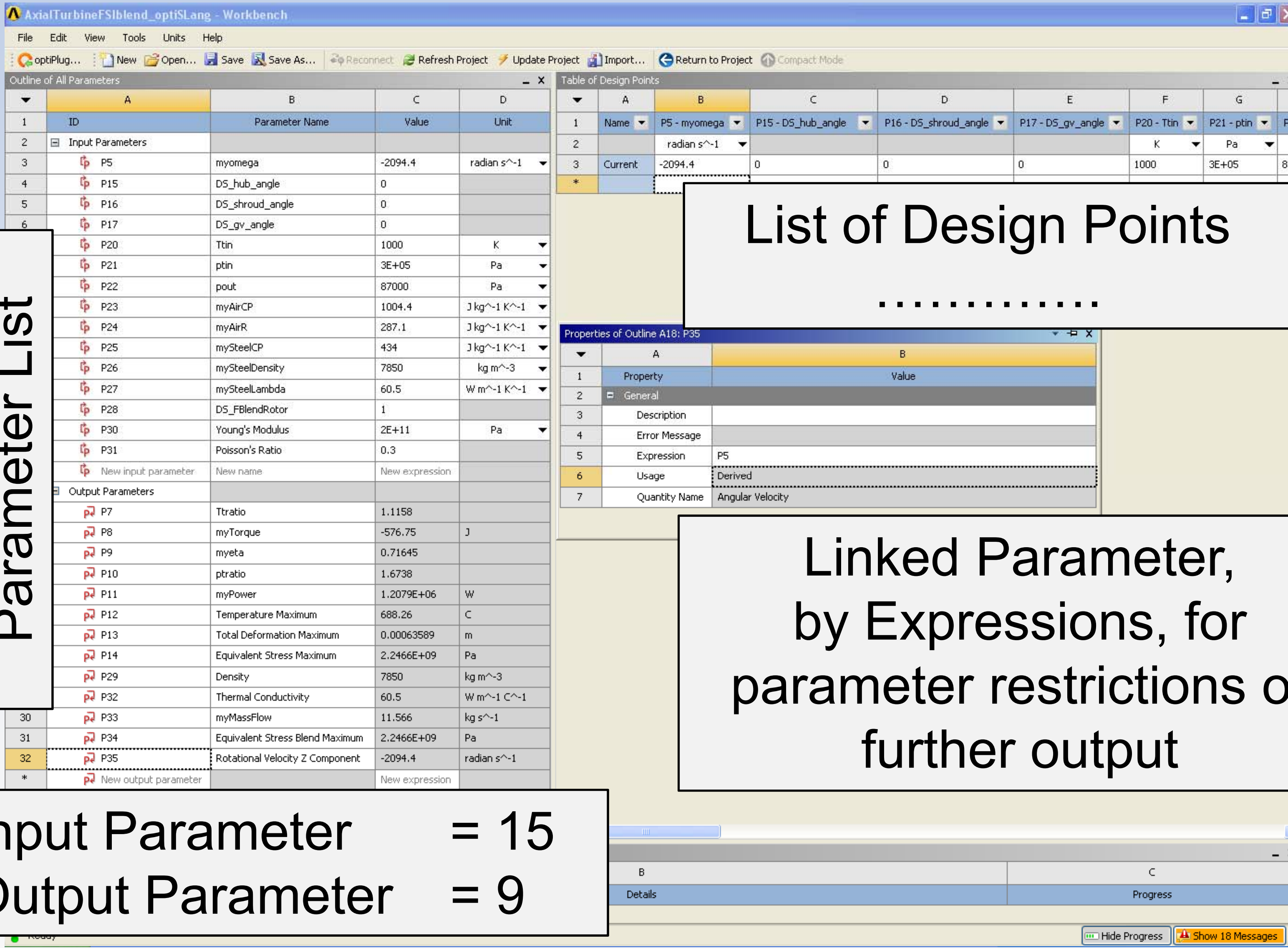
- Extended solver support
- Embedded analysis tool
- Automatic user interaction

Parameterization of the Geometry



Define Parameter
1. Rotation Angle, Guide Vane
2. Rot. Angle, Shroud Profile
3. Rot Angle, Hub Profile

Parameter Manager



Parameter List

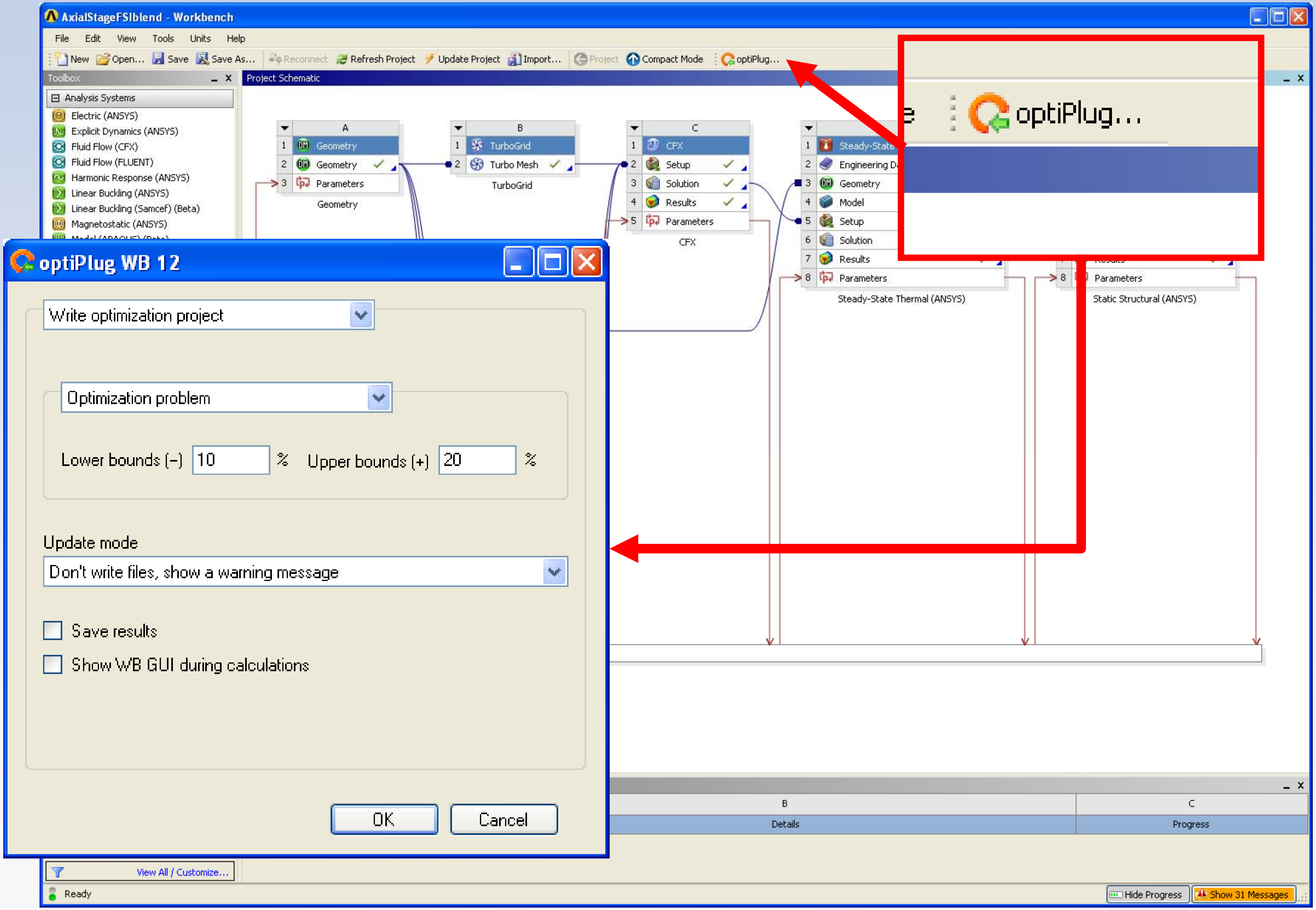
List of Design Points

…………..

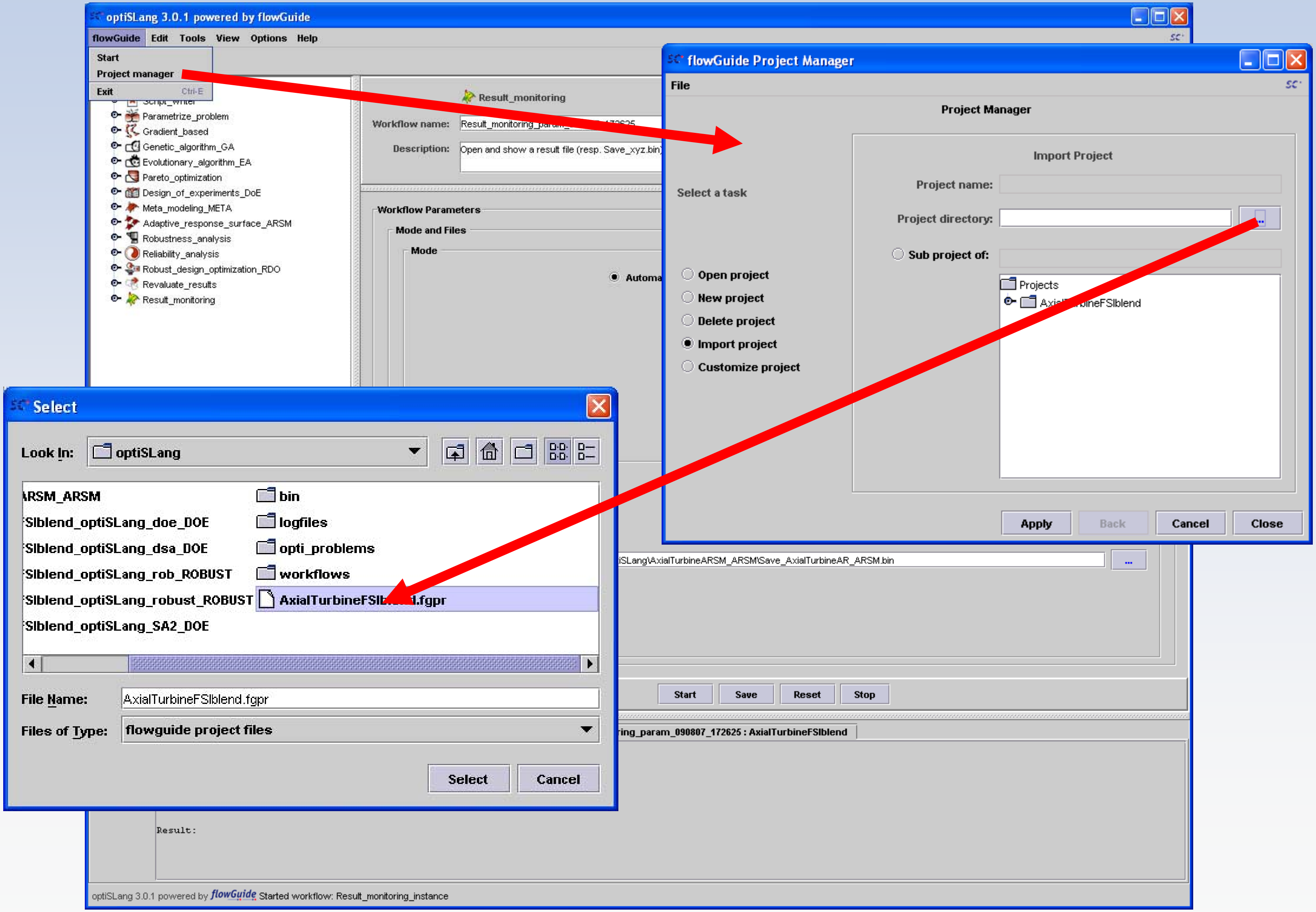
Linked Parameter, by Expressions, for parameter restrictions or further output

Input Parameter = 15
Output Parameter = 9

Workbench Interface to optiSLang



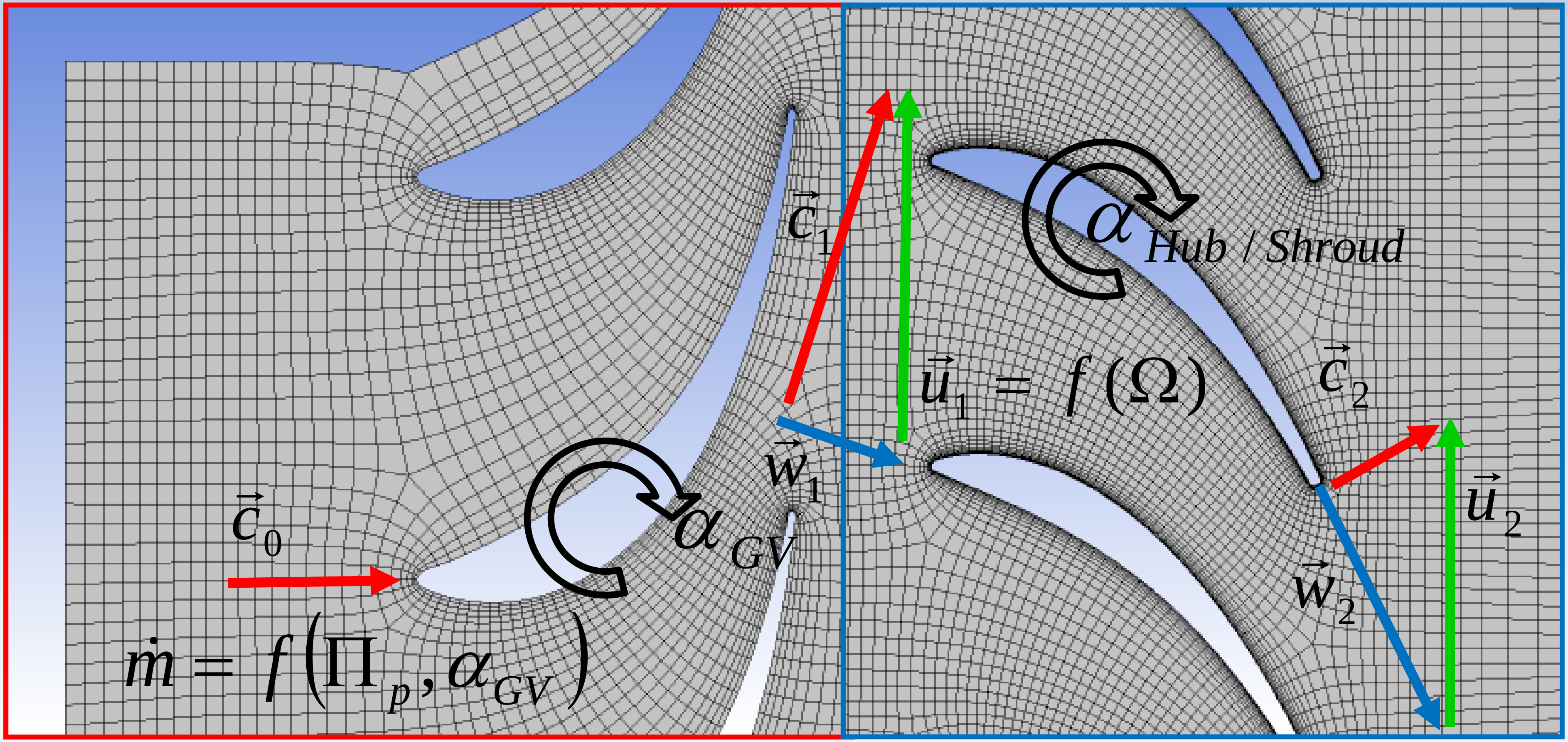
Workbench Interface to optiSLang



Parameter Attributes

Input Parameter	Parameter Name	Initial Value	Type
Blade Angels	$\alpha_{GV},\alpha_{Hub},\alpha_{Shroud}$	0°, 0°, 0°	deterministic
Rotational Velocity of Rotor	Ω	-2094 [rad/s]	deterministic
Rotor Blend Radius	r_{Blend}	1 [mm]	deterministic
Total Temperature Inlet	$T_{t,Inlet}$	1000 [K]	deterministic
Total Pressure Inlet	$p_{t,Inlet}$	400 [kPa]	deterministic
Pressure Outlet	p_{out}	187 [kPa]	stochastic
All Material Properties	-	-	stochastic
Output Parameter	**Parameter Name**	**Initial Value**	**Target**
Total Temperature Ratio	$\Theta_T=T_{t,Inlet}/T_{t,Outlet}$	1.115	-
Total Pressure Ratio	$\Pi_p=p_{t,Inlet}/p_{t,Outlet}$	1.673	-
Torque/Power at Rotor	M_P, P	-577 [Nm], 1.21 [MW]	maximize
Mass Flow Rate	m	11.56 [kg/s]	-
Isentropic Efficiency	η	71.64 [%]	maximize
Maximal v. Mises Stress	σ_{max}	218.6 [MPa]	below limit

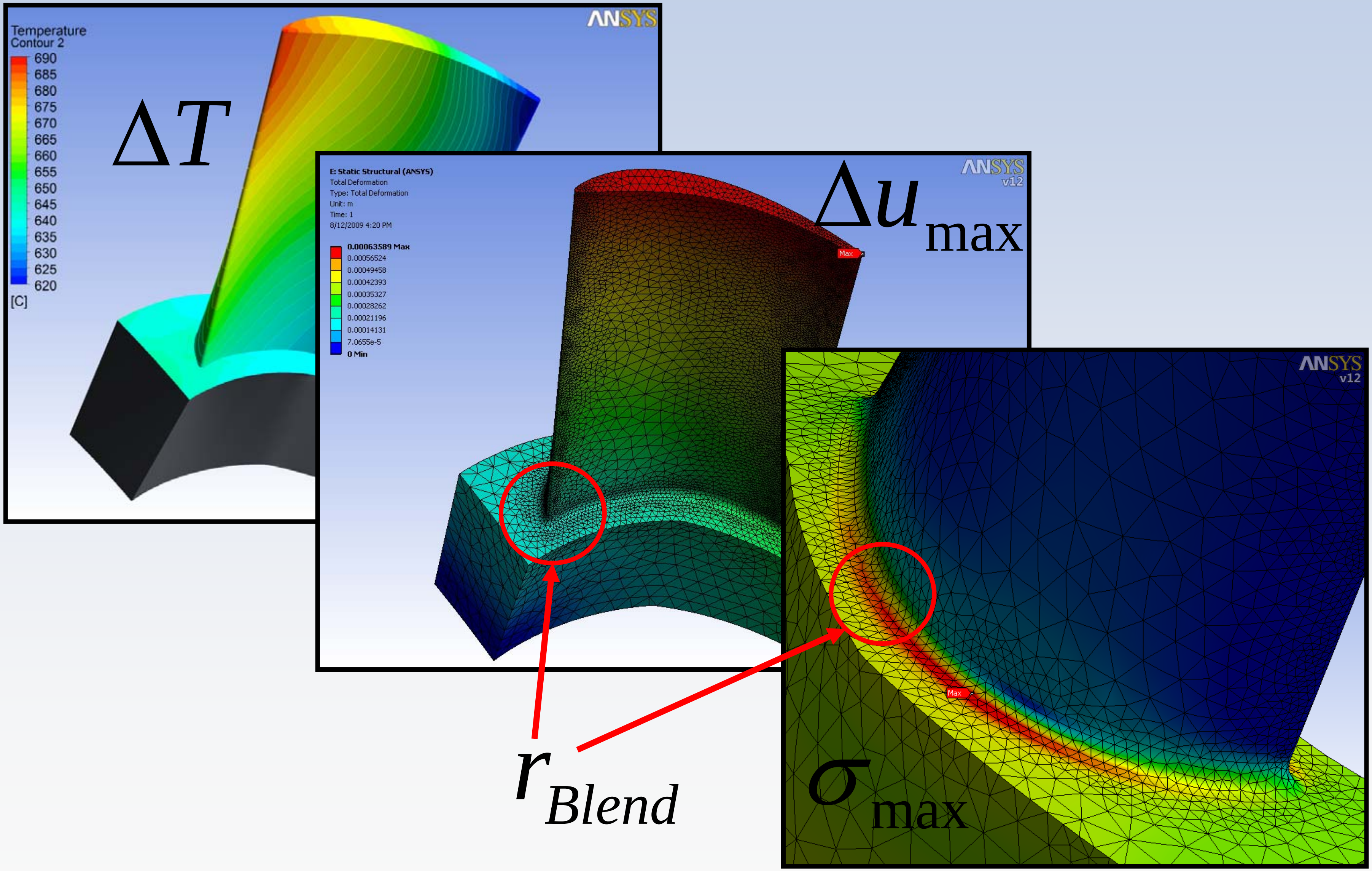
Parameter Physics, Fluid Flow

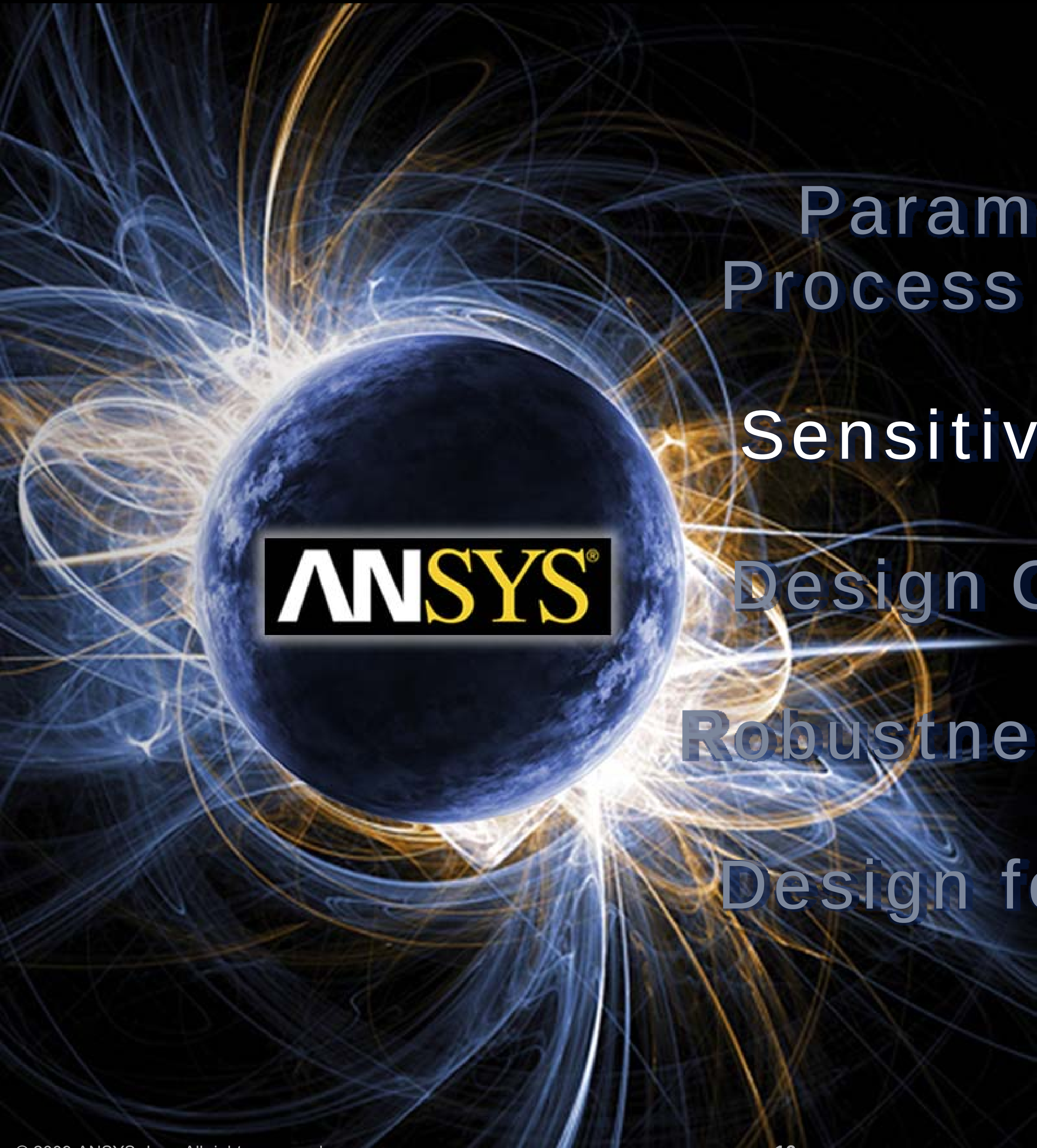


$$\boxed{\eta = f(\Theta_T, \Pi_p)}$$

$$\boxed{P, M_P \sim \dot{m} \cdot \underset{1-2}{\Delta}(u \cdot c_u)}$$

Parameter Physics, Mechanic





Parameterization
Process & Geometry

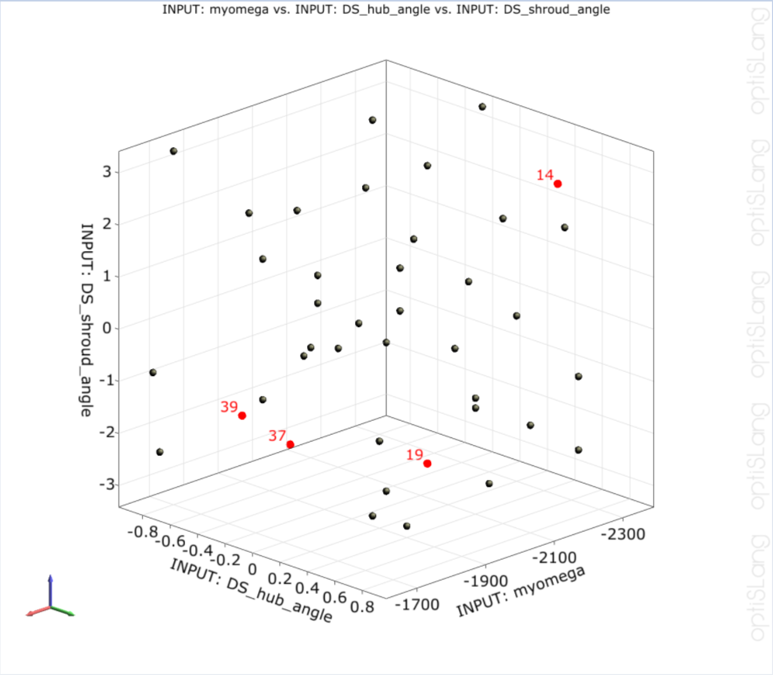
Sensitivity Analysis

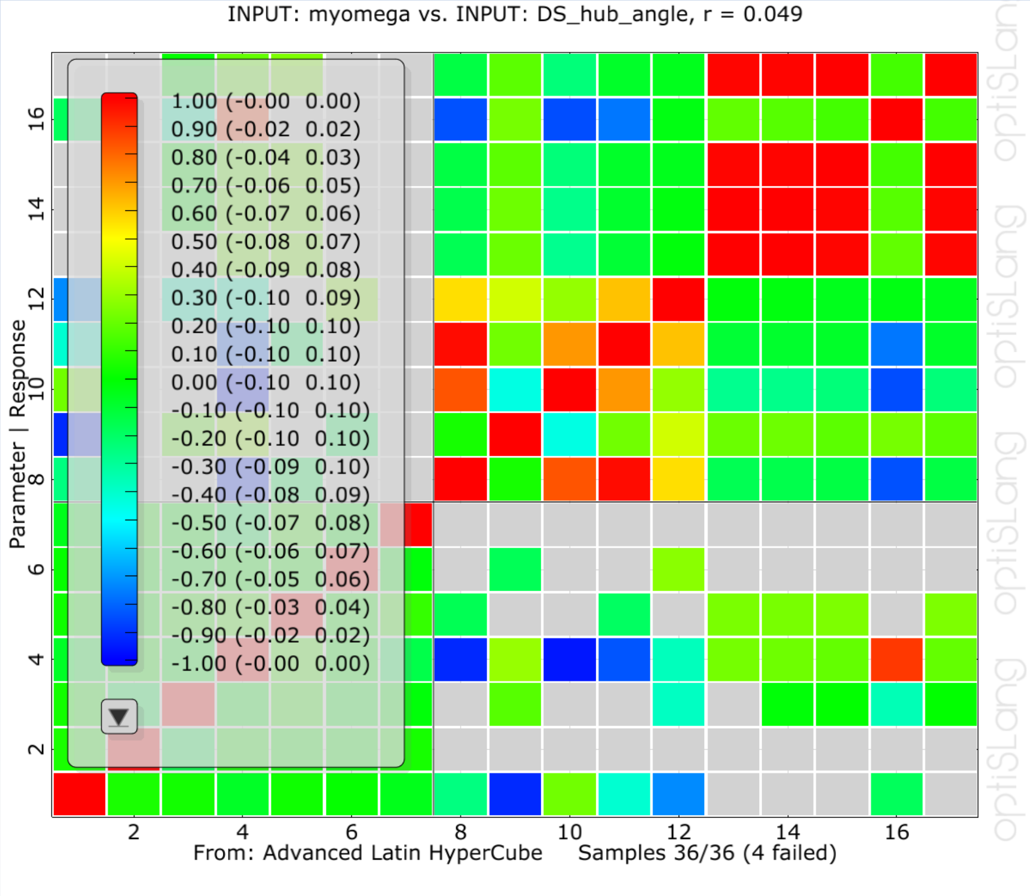
Design Optimization

Robustness Evaluation

Design for Six Sigma

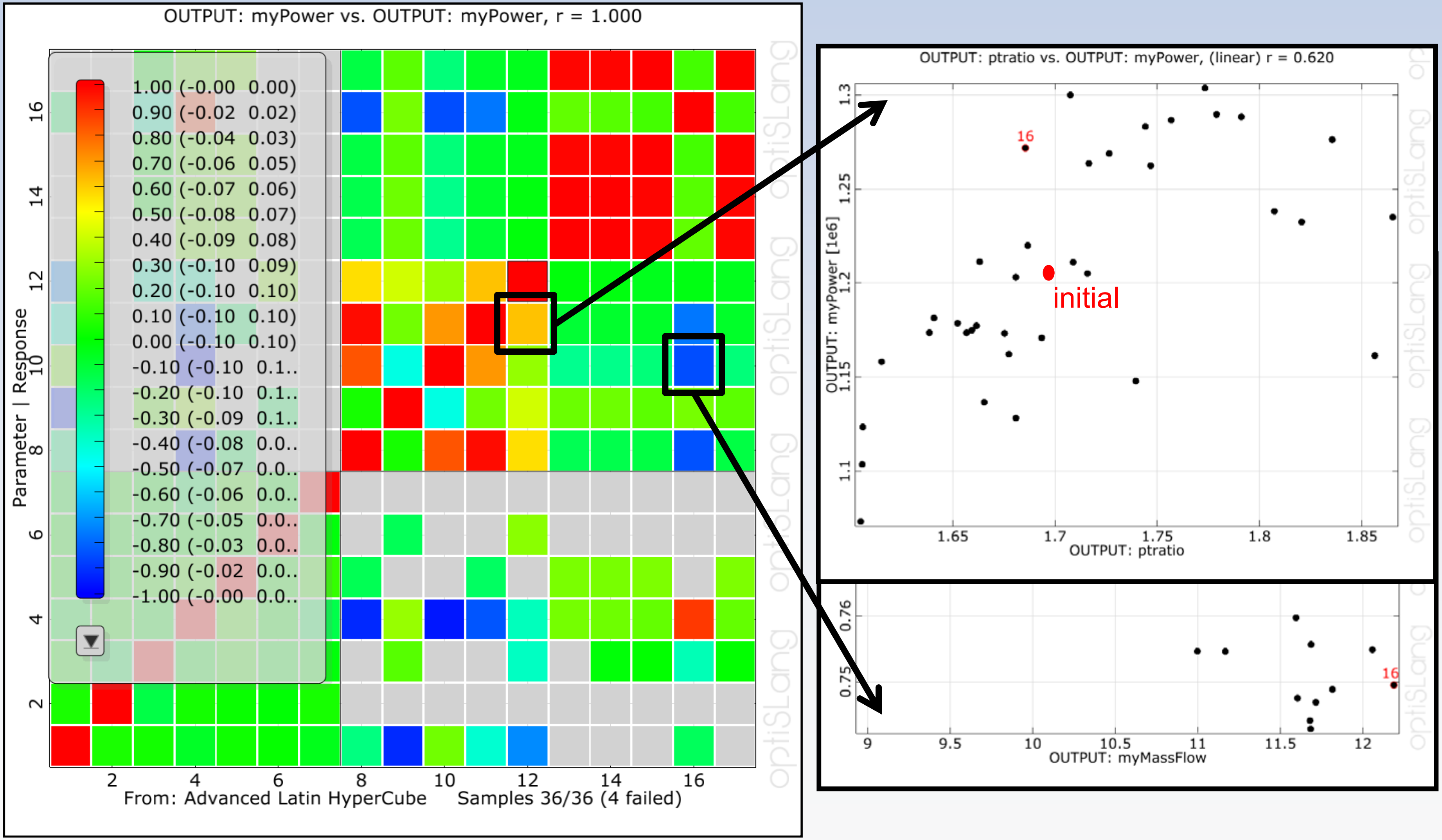
Latin Hypercube and Confidences



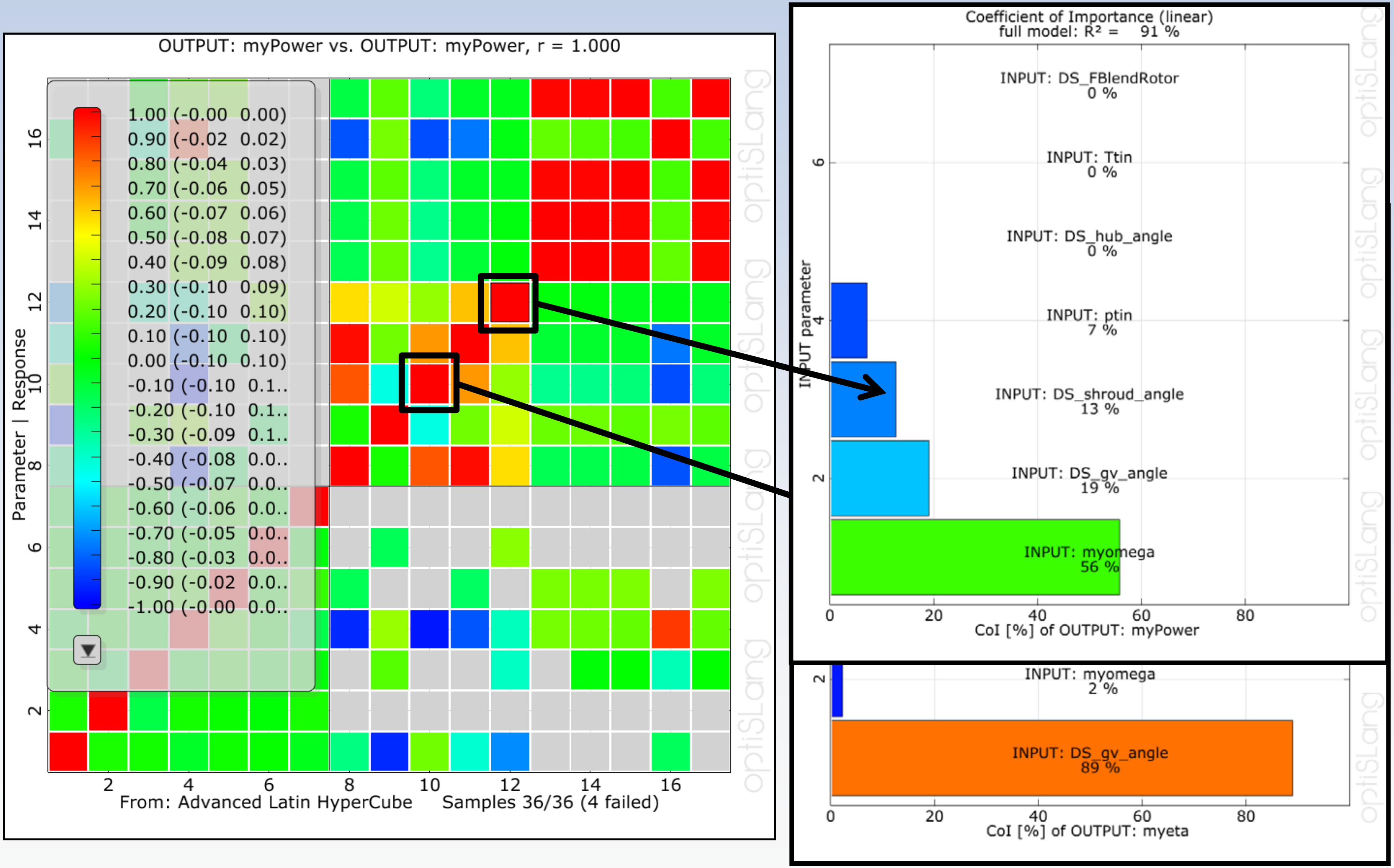


- **n = 7 design variables**
- **N = 40 design evaluations (4 failed)**
- **Confidence levels are quite acceptable**

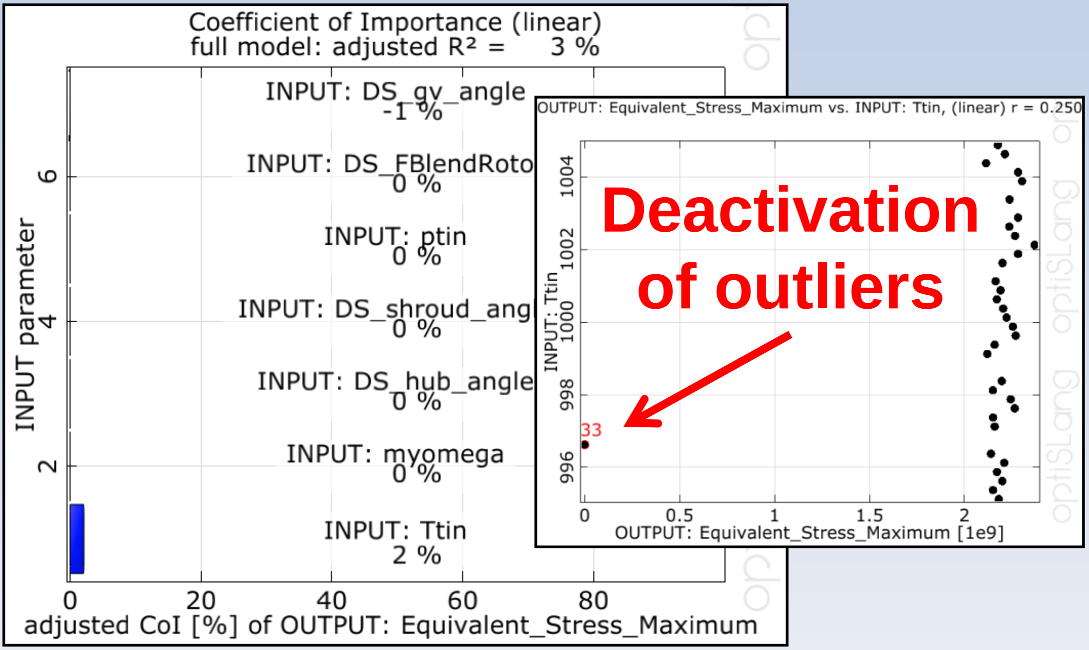
Confidences, Anthill Plots

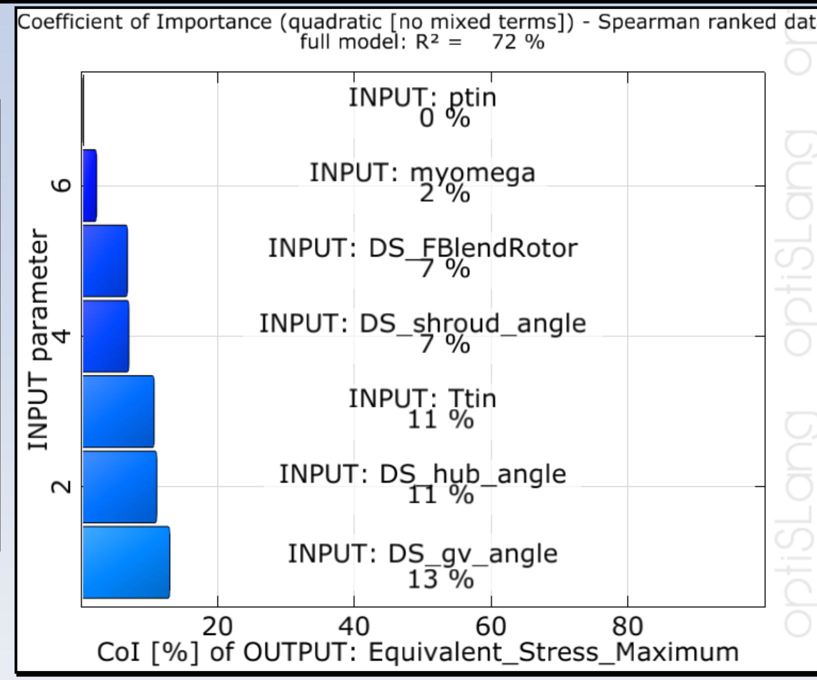


Coefficient of Importance, CoI



Coefficient of Importance Quadratic Regression

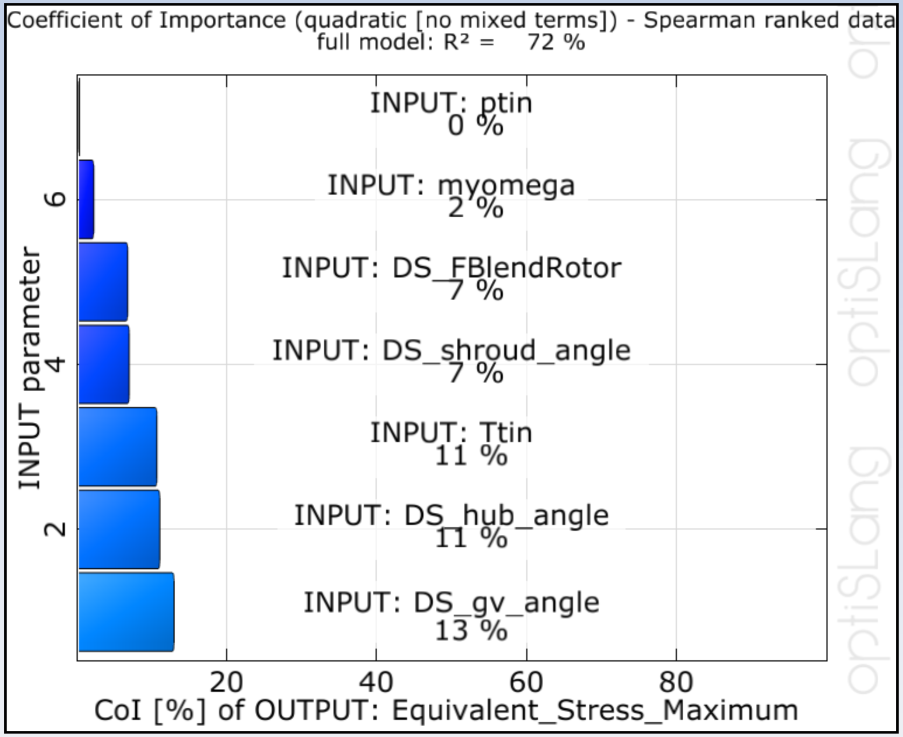


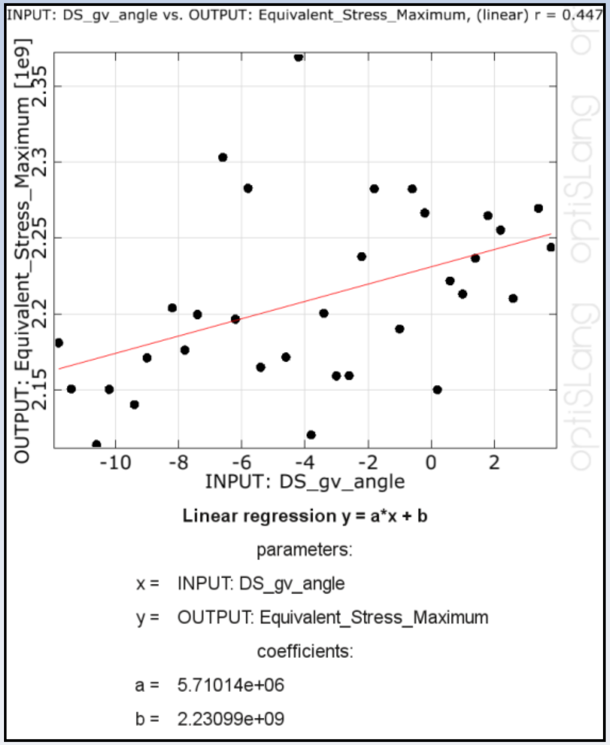


- **Filtered parameters vs. all parameters**
- **Linear vs. nonlinear monotonic and quadratic regression**
- **Adjusted vs. non-adjusted coefficient of determination**

72% variance of the stress variation can be explained by the given n = 7 design variables

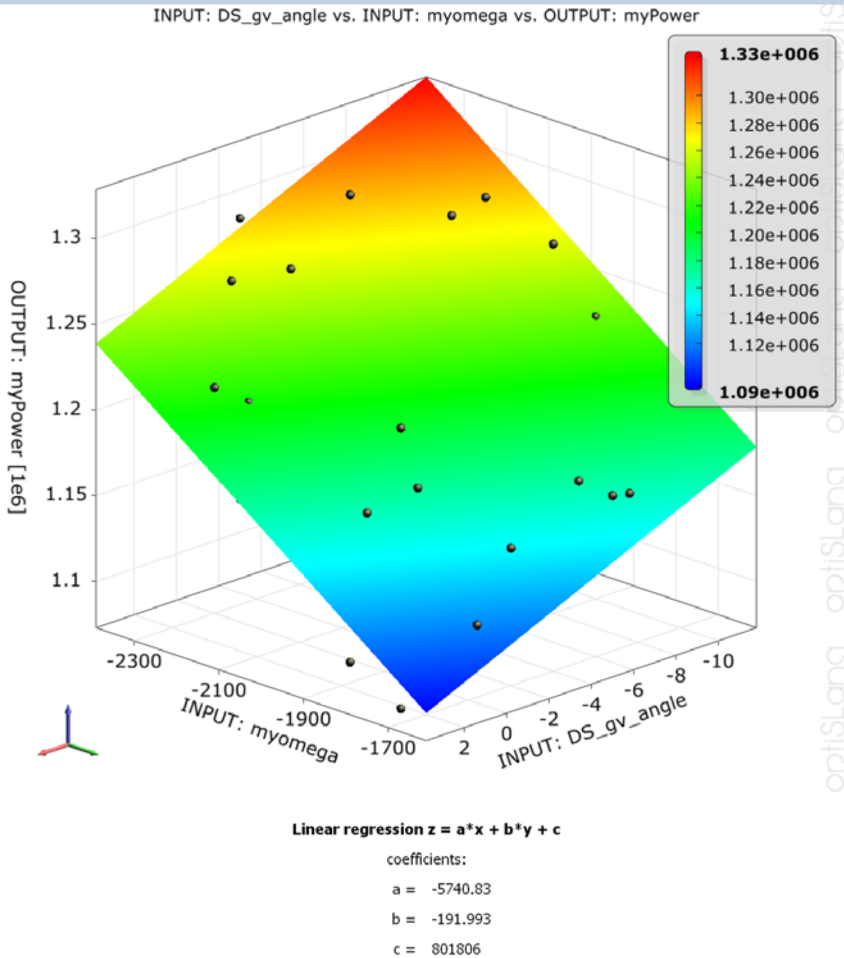
Coefficient of Importance Quadratic Regression



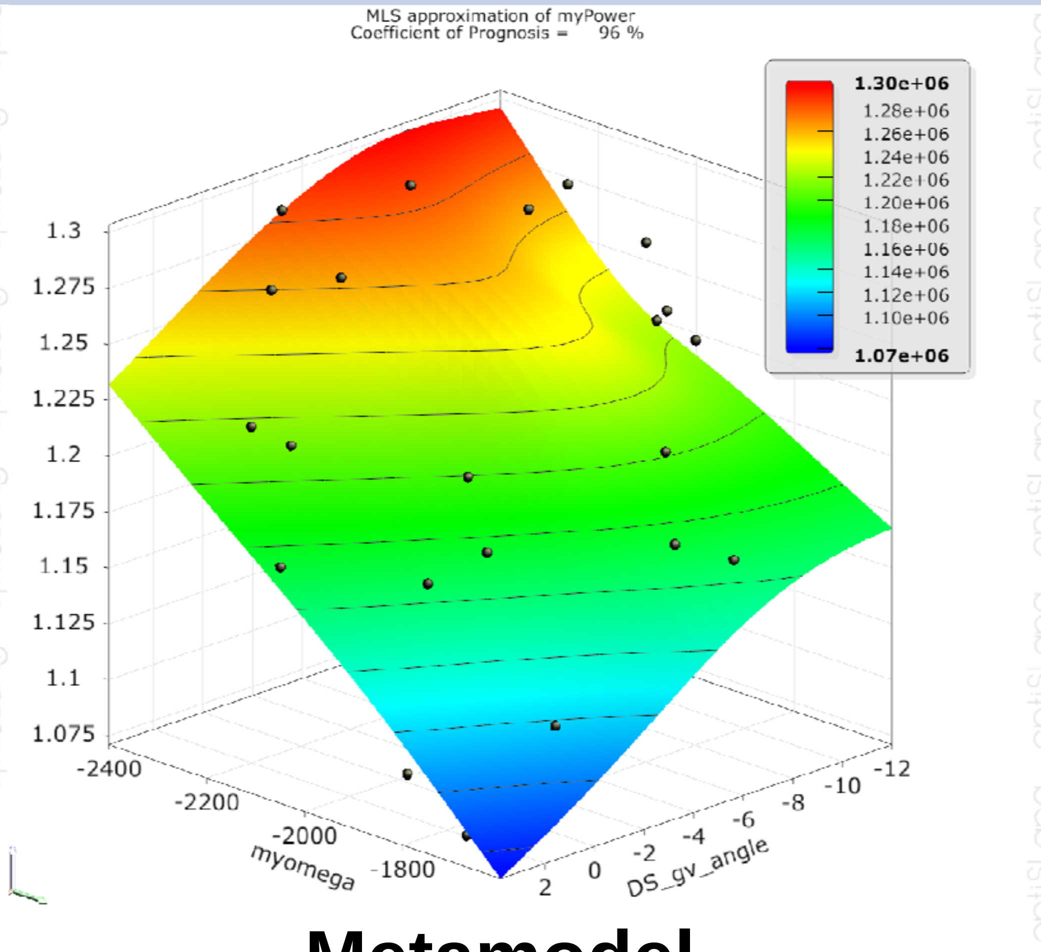


- **Most important parameter of the equivalent stress is guide vane angle according the Coefficient of Importance**
- **Anthill plot shows slow correlation**
- **Verification using CoP/MoP**

Metamodel of Prognosis, MoP

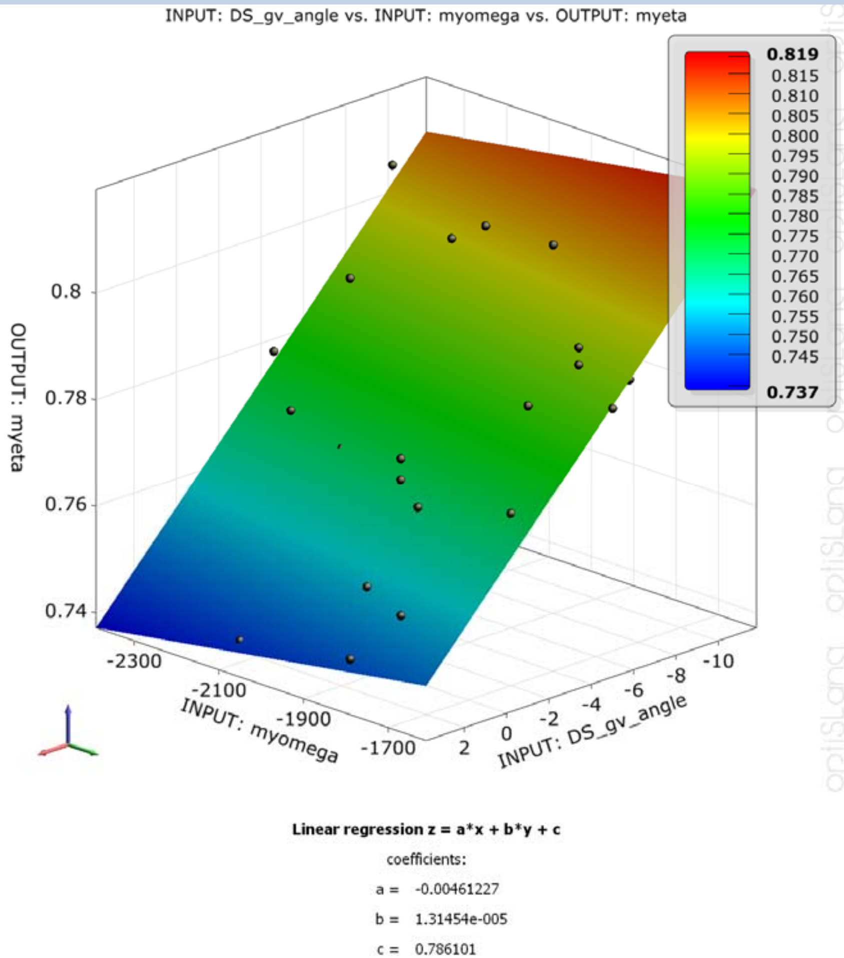


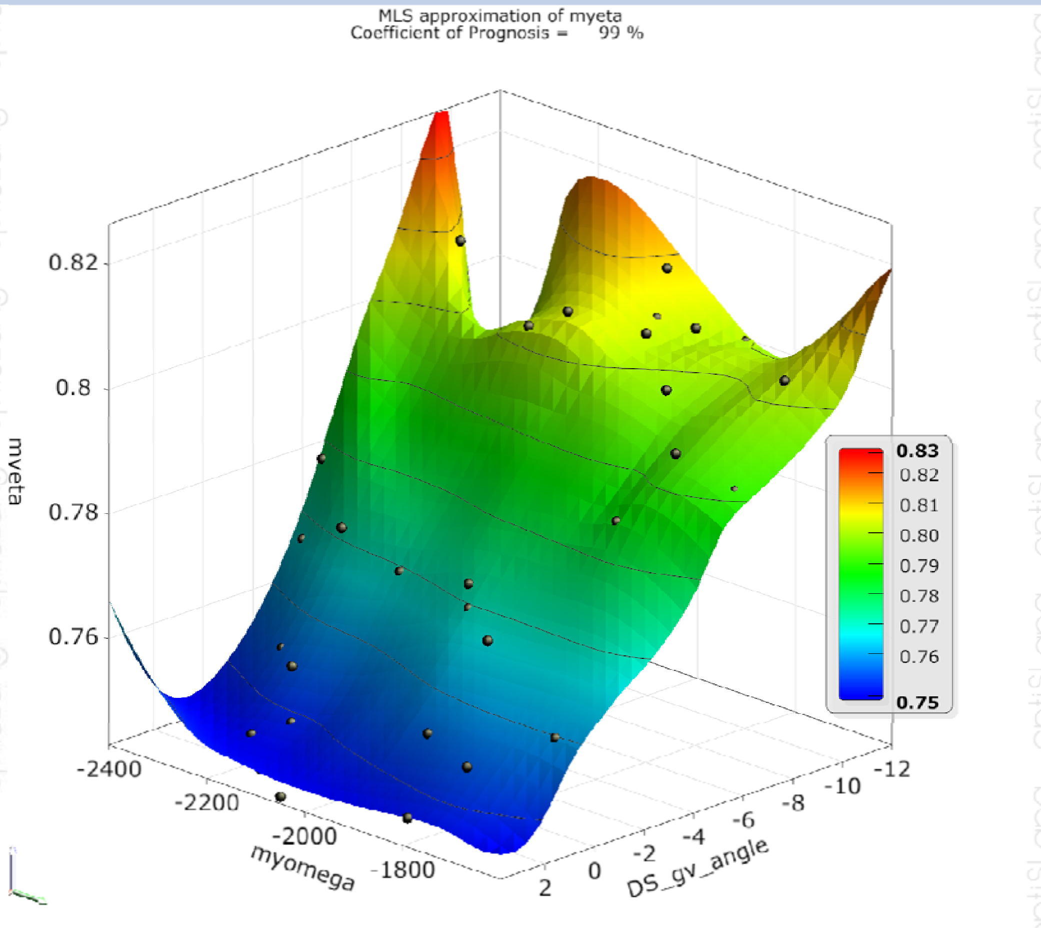
Response Surface
Output: Power



Metamodel
Output: Power

Metamodel of Prognosis, MoP

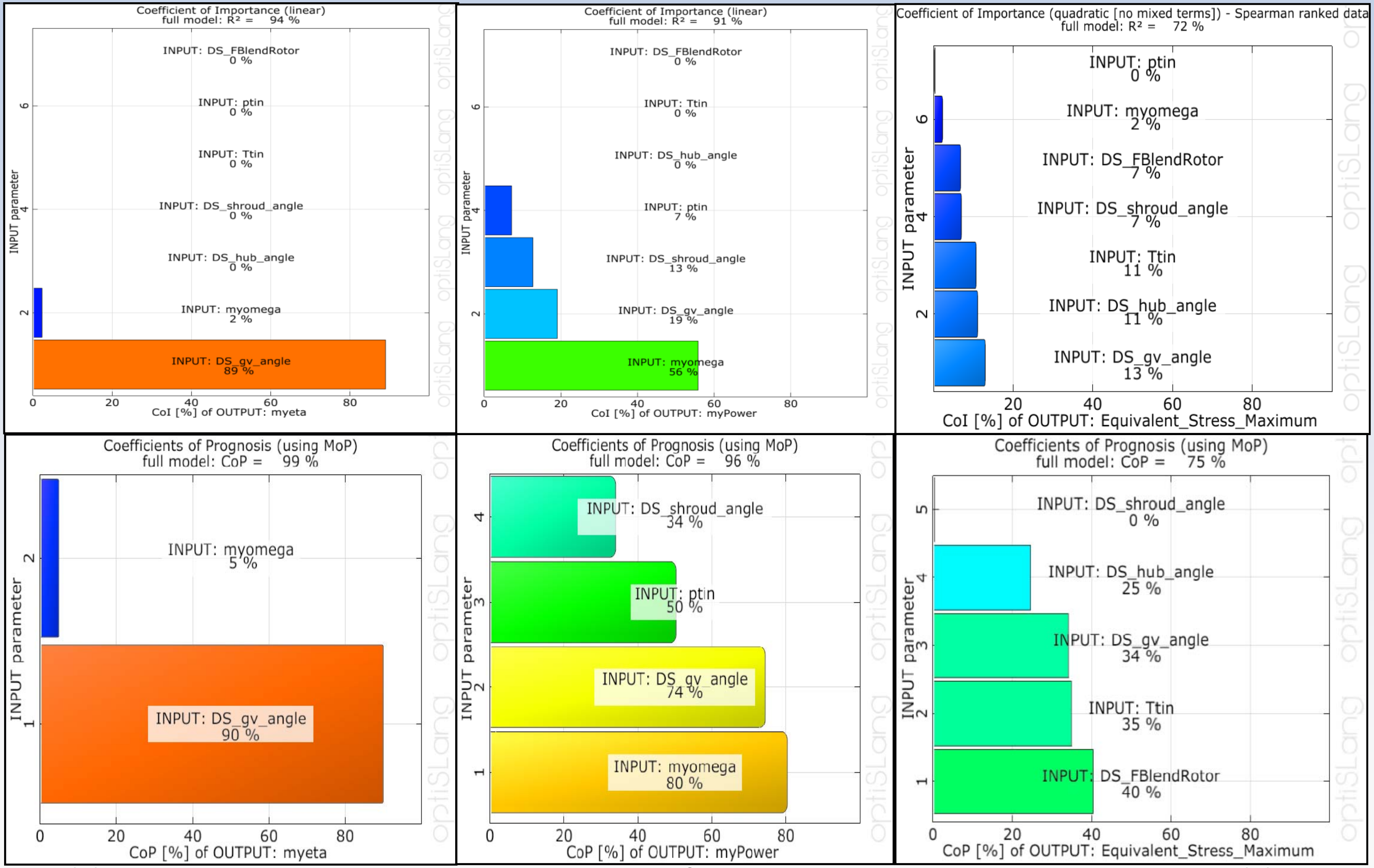




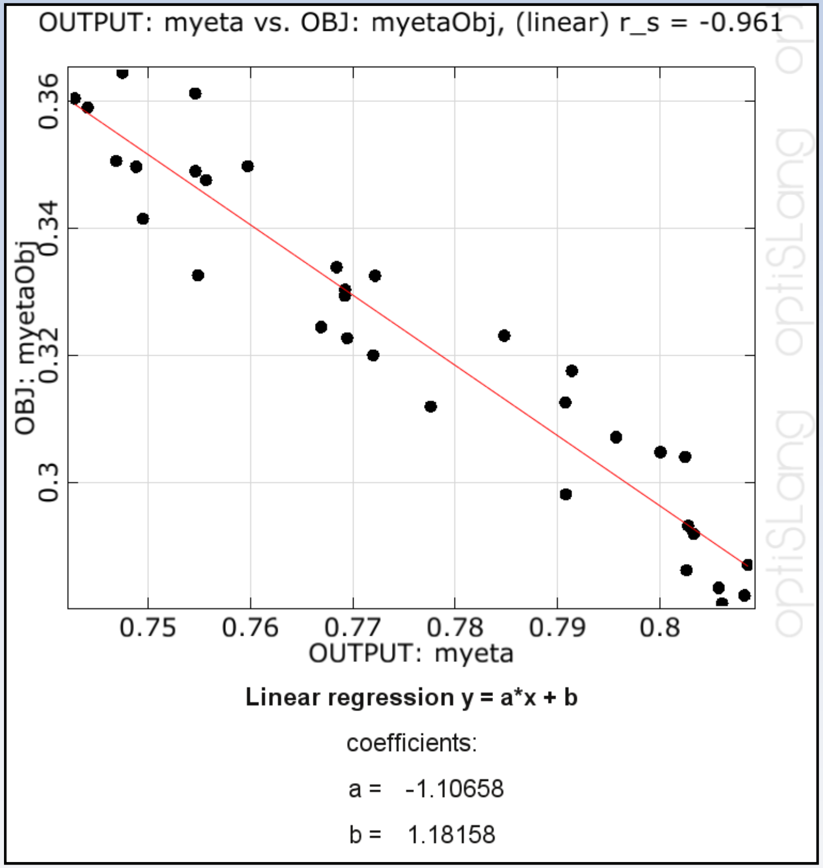
Response Surface
Output: Efficiency

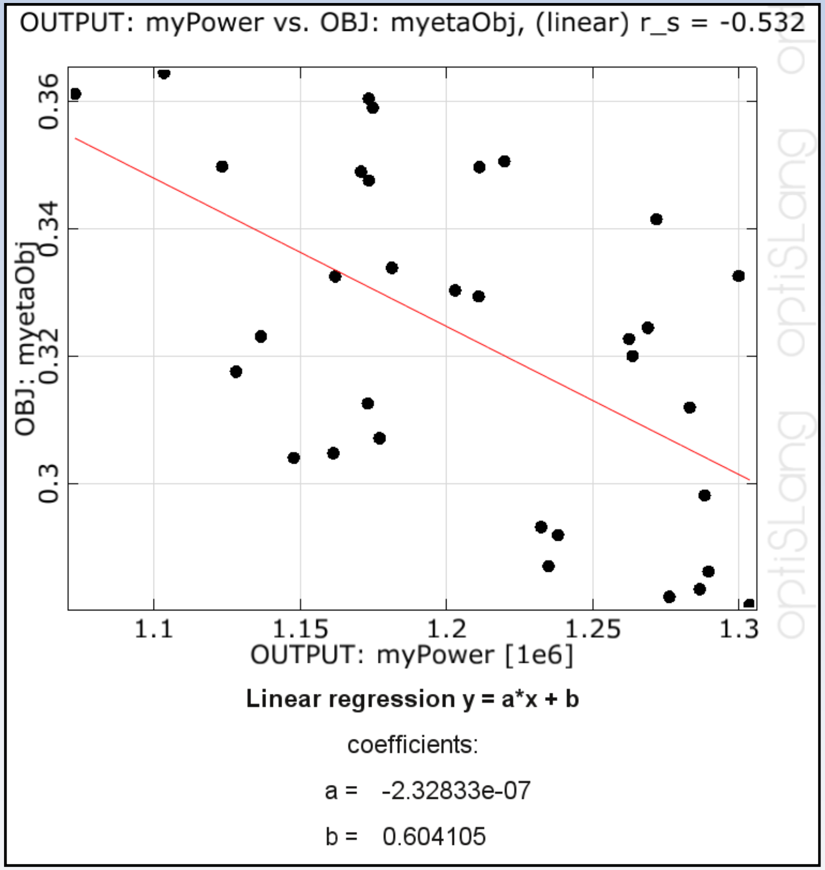
Metamodel
Output: Efficiency

Coefficient of Importance, CoI vs. Coefficient of Prognosis, CoP



Anthill Plots Objective



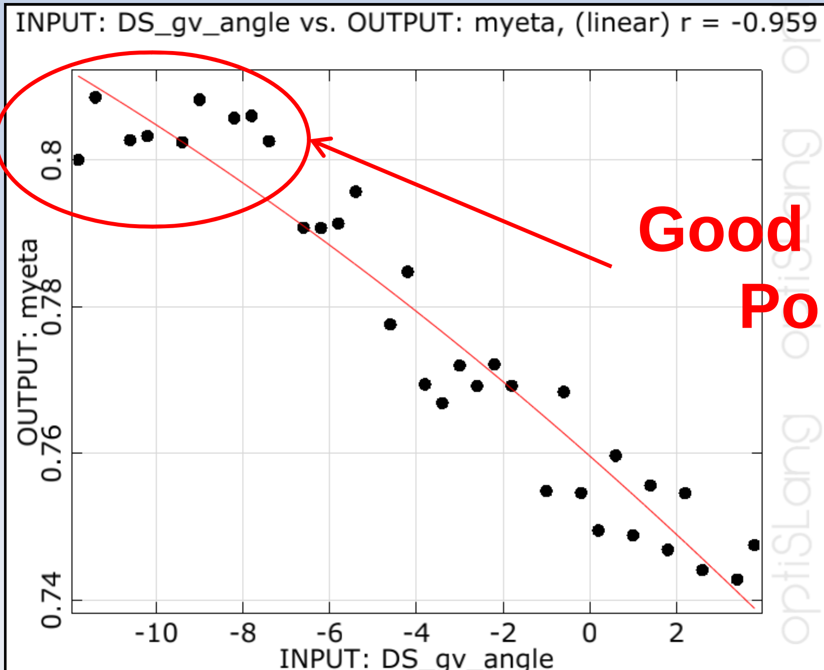


Target Function for Optimization:

$$f_{\text{Target}} = (1-\eta) + \frac{1}{4}\cdot\left(1-\frac{P}{2[MW]}\right) \overset{!}{=} \min$$

Weighted objective mainly depends on efficiency

Anthill Plots Objective



Quadratic regression y = a*x² + b*x + c

parameters:

x = INPUT: DS_gv_angle

y = OUTPUT: myeta

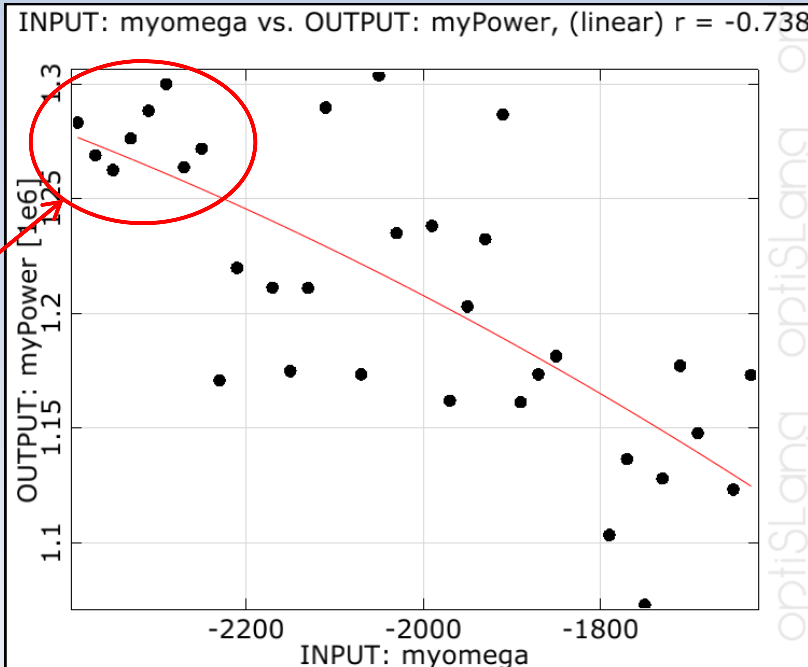
coefficients:

a = -6.91412e-05

b = -0.00520764

c = 0.759667

Good Design Points



Quadratic regression y = a*x² + b*x + c

parameters:

x = INPUT: myomega

y = OUTPUT: myPower

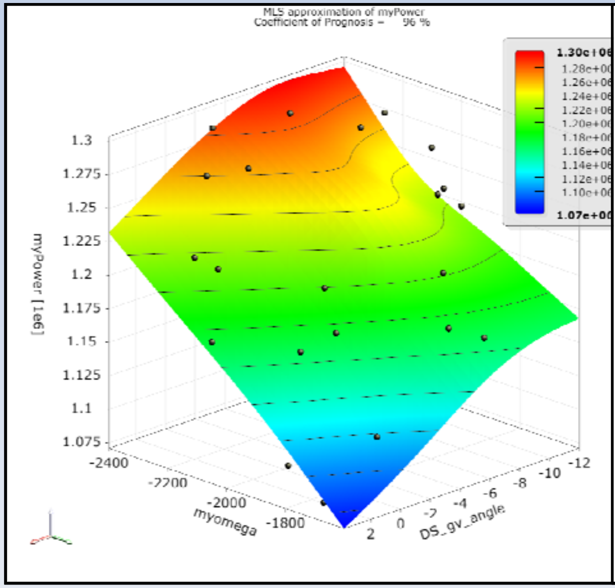
coefficients:

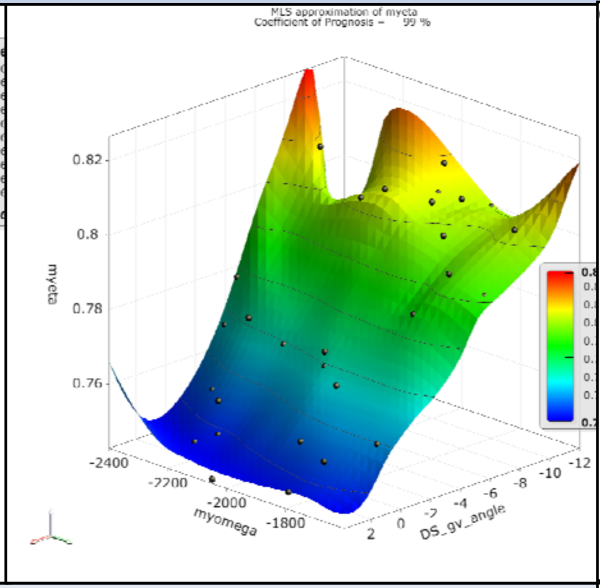
a = -0.0630151

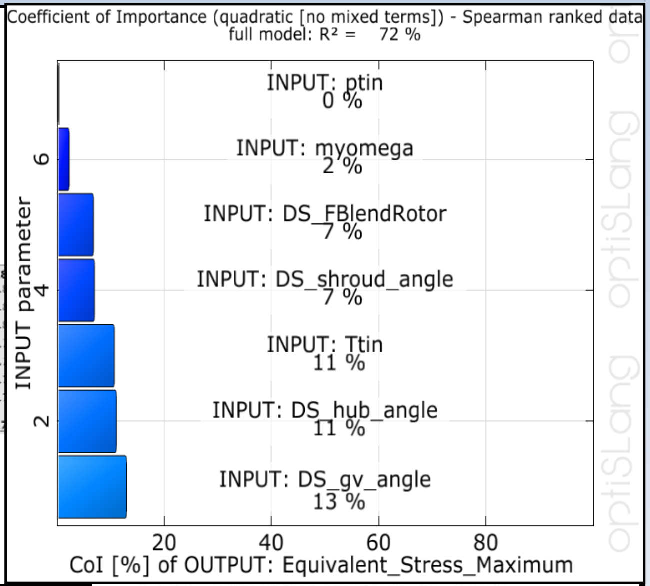
b = -453.209

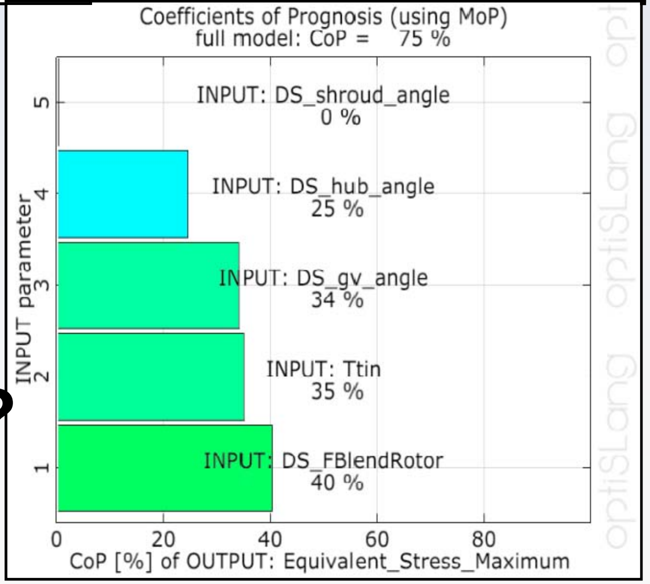
c = 553468

Sensitivity analysis shows optimization potential to increase efficiency and power









- **Is Sensitivity reliable, CoI?**
- **Is Sensitivity reliable, CoP?**
- **Is Sensitivity plausible, physics?**

Parameterization
Process & Geometry

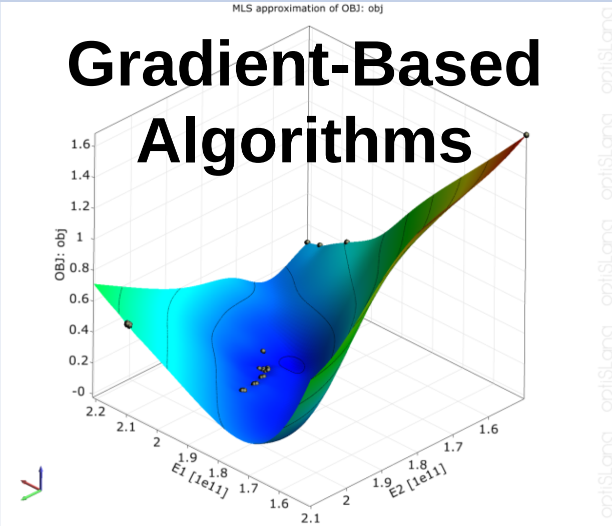
Design of
Experiments

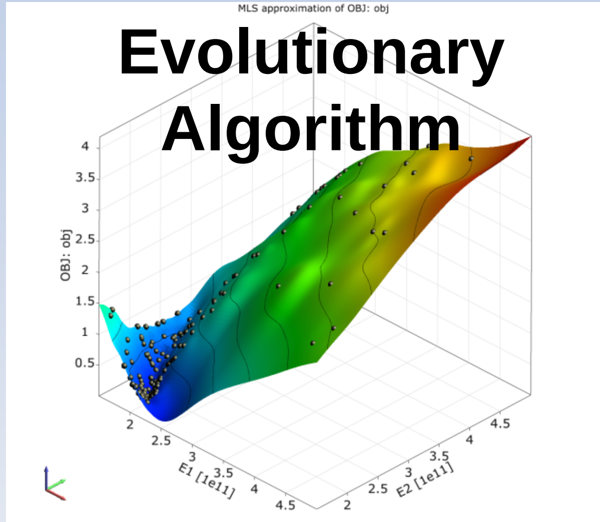
Design Optimization

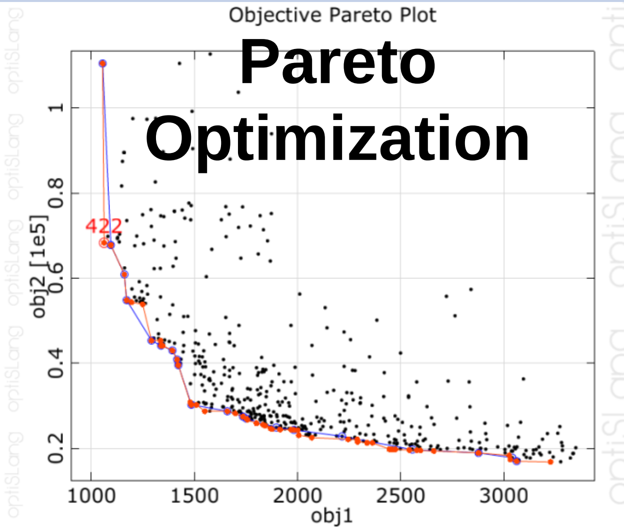
Robustness Evaluation

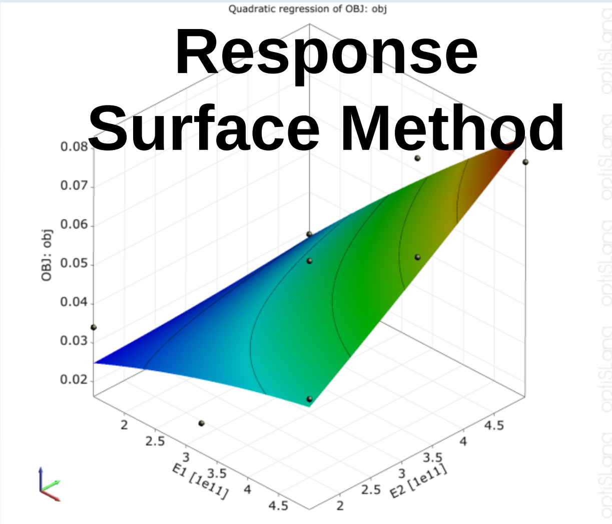
Design for Six Sigma

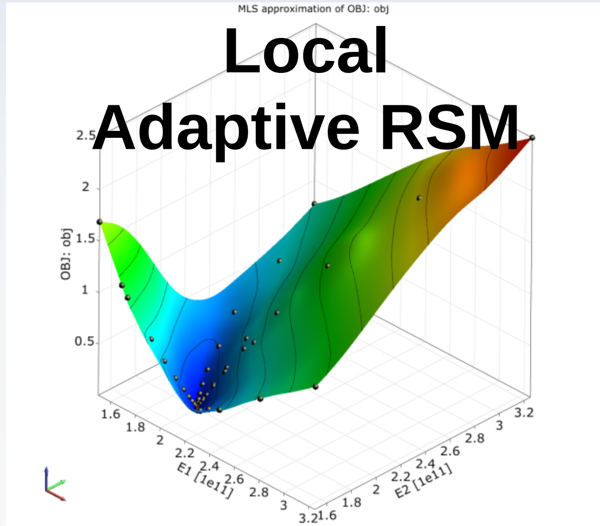
Nonlinear Optimization, Algorithm

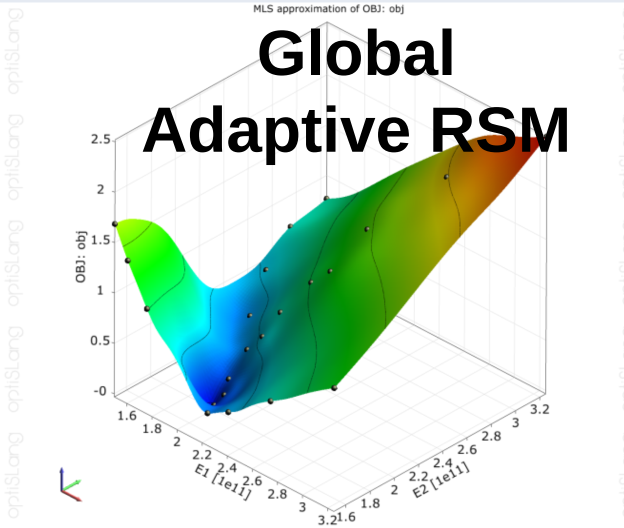








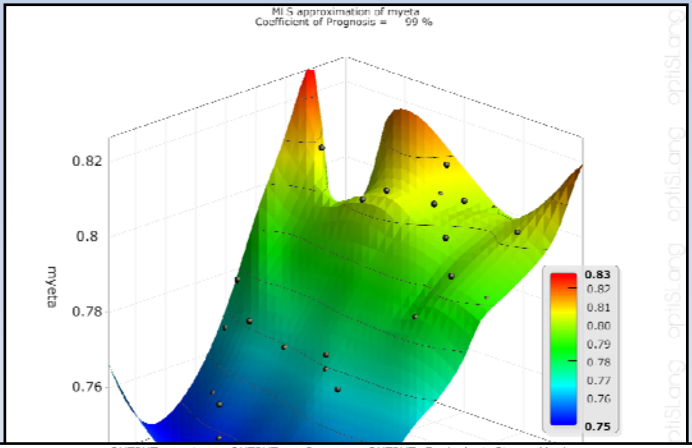


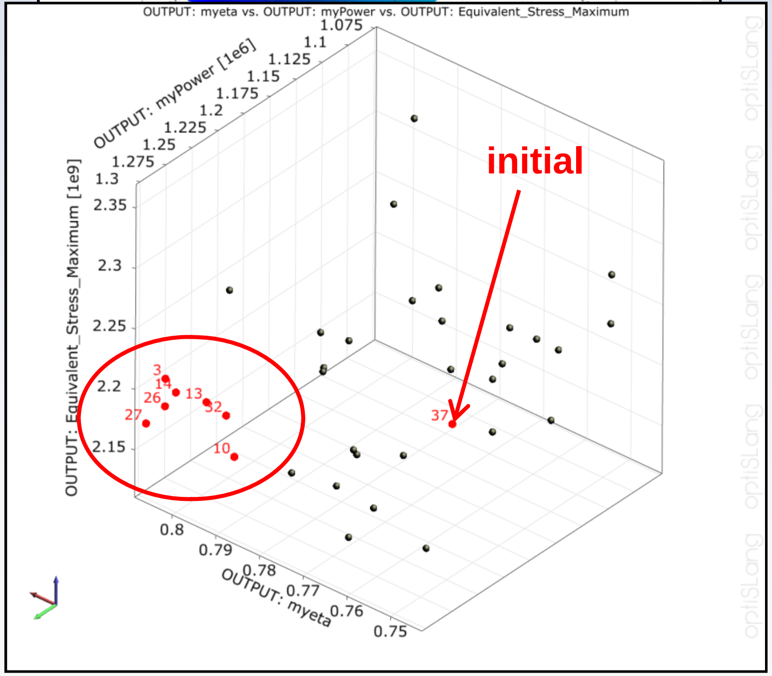


Optimization Strategy

Sensitivity Analysis

- Shows Potential
- Non convex target
- No parameter reduction



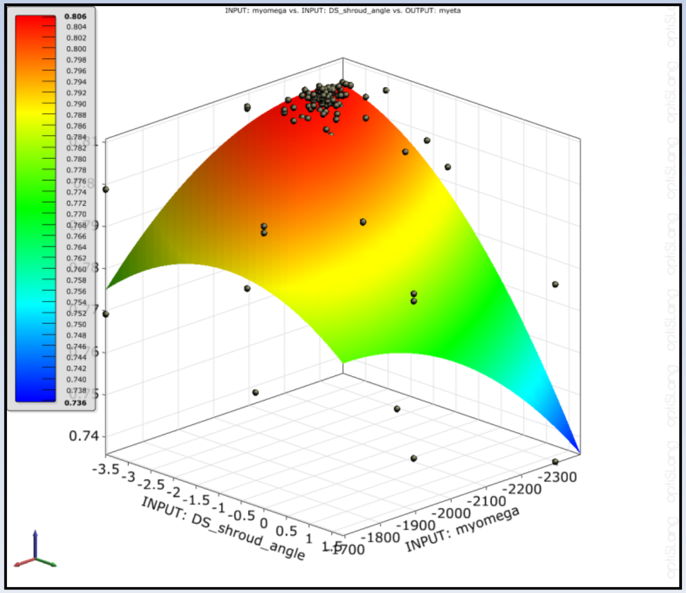


Strategy:

- Global search, EA
- Start population from DoE
- Local improvement, ARSM

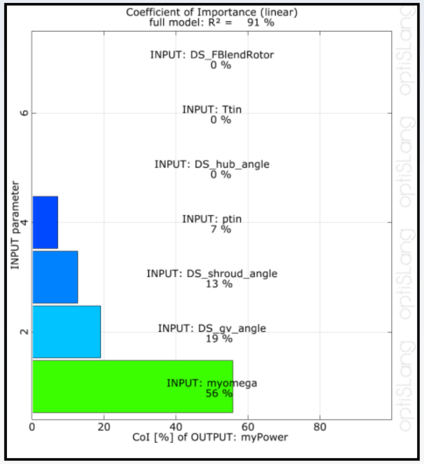
Sensitivity Analysis

- Shows Potential
- Convex target
- Parameter reduction



Strategy:

- Global search, sub space, ARSM
- Local improvement, full space, EA
- Start population from ARSM

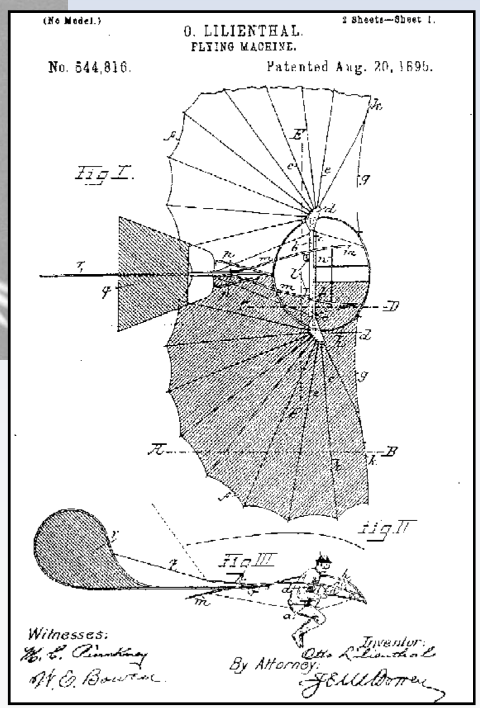


Evolutionary Algorithms (EA)

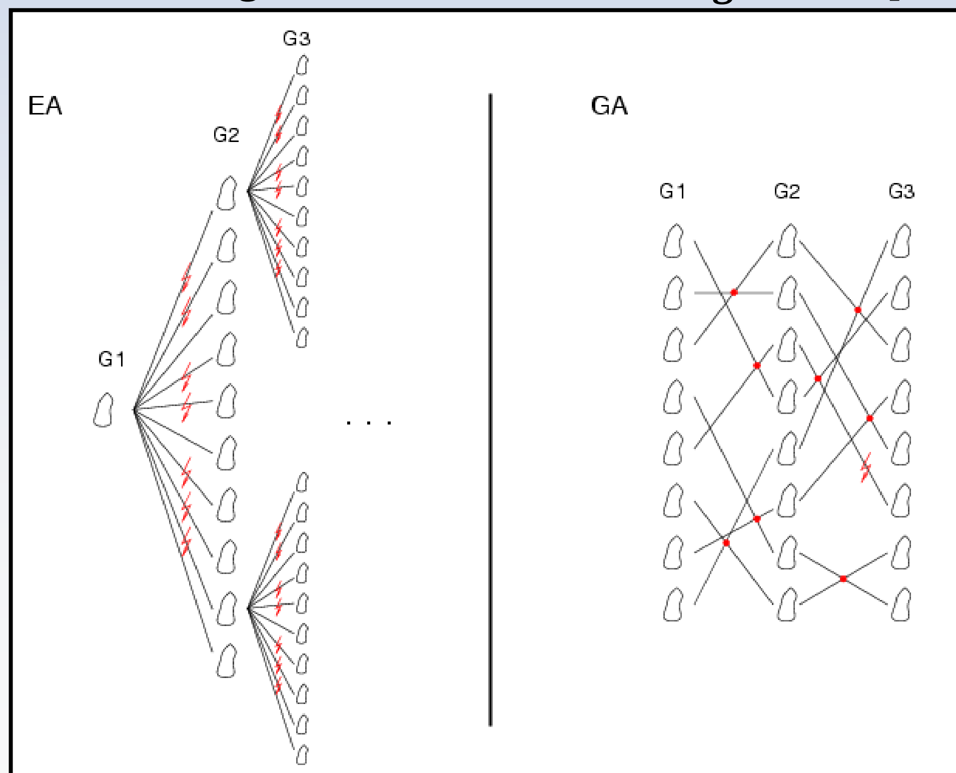
Optimization in Nature:

- Survival of the fittest

- Evolution due to mutation, recombination and selection

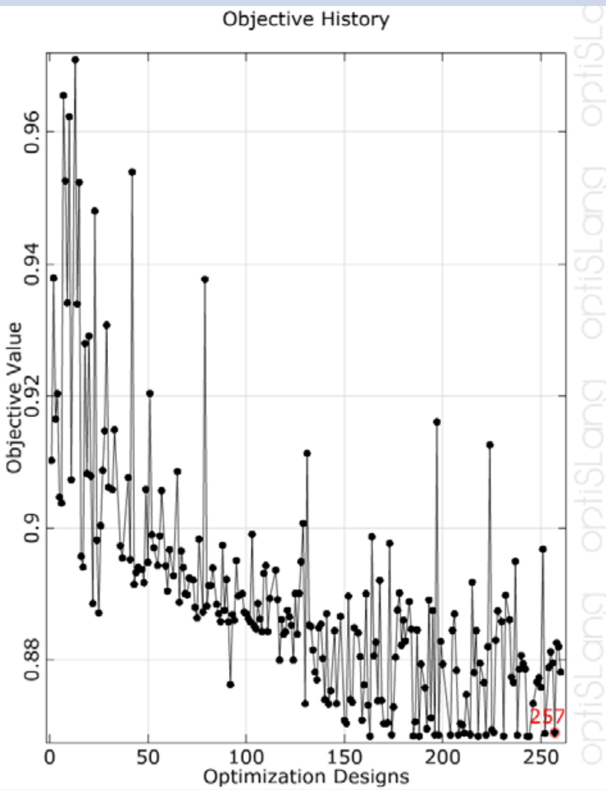


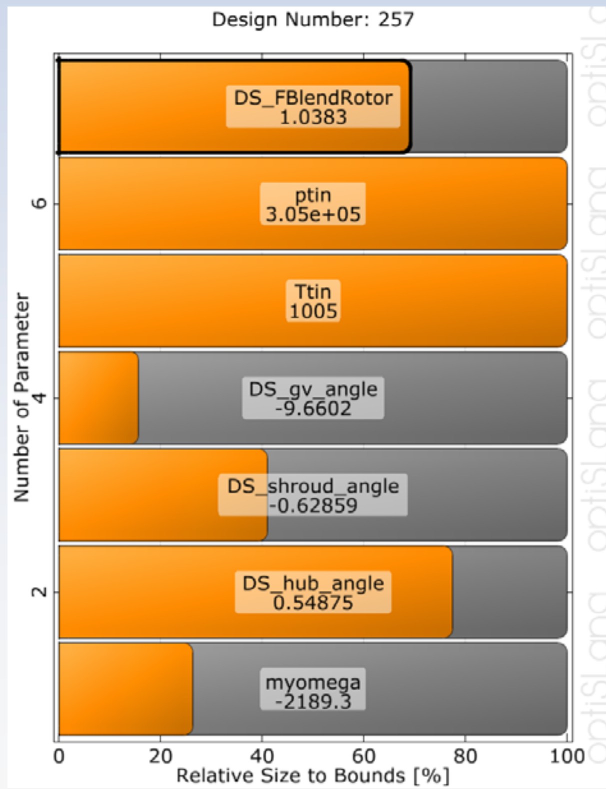
Evolution Algorithms [EA] **Genetic Algorithms [GA]**

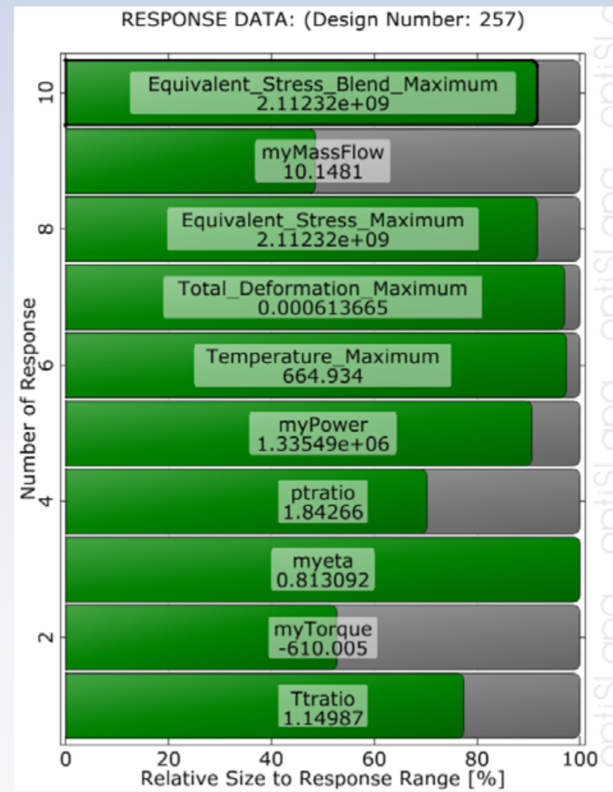


Evolutionary Algorithms (EA)

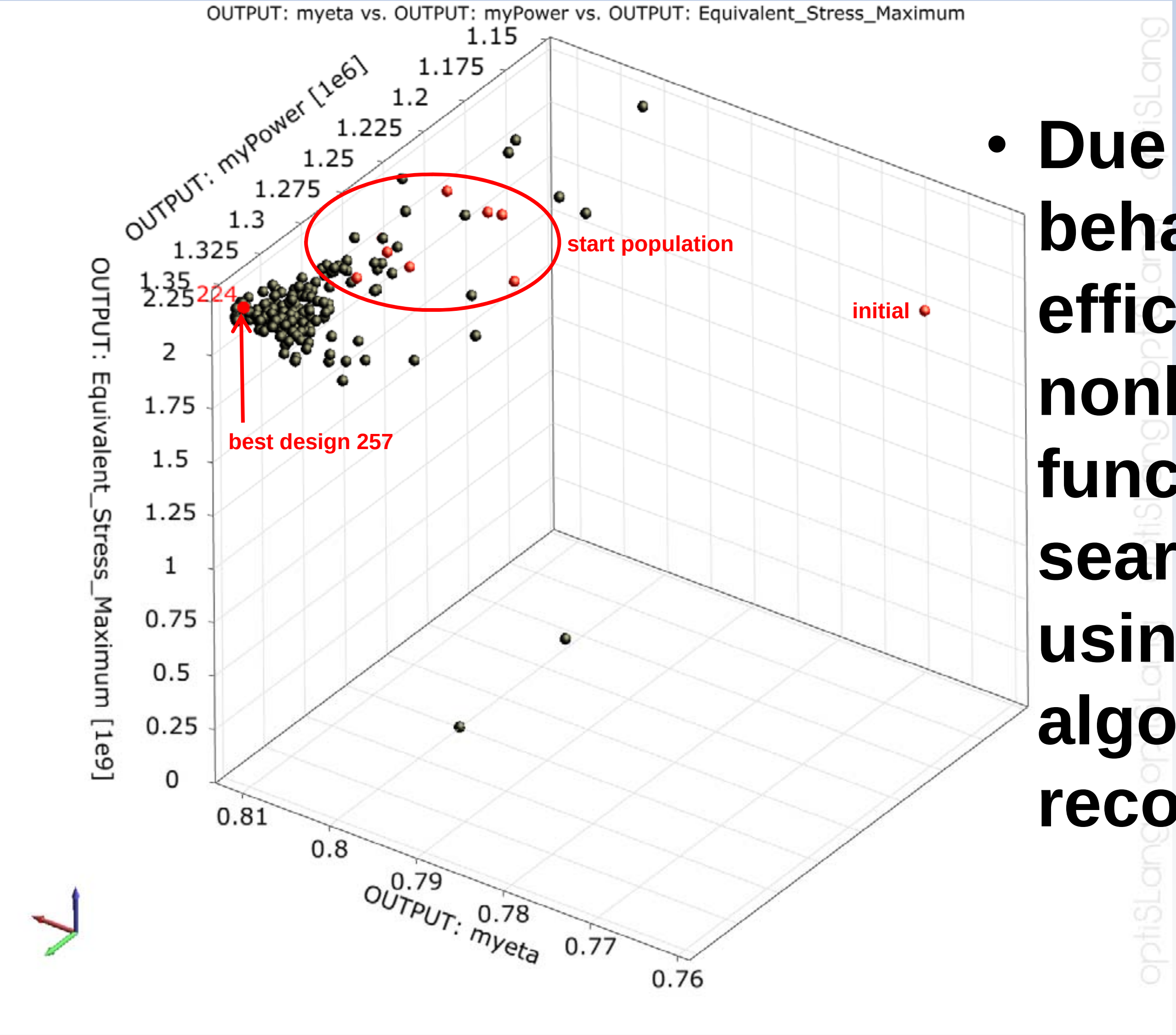
- **History of the Evolutionary Algorithm**





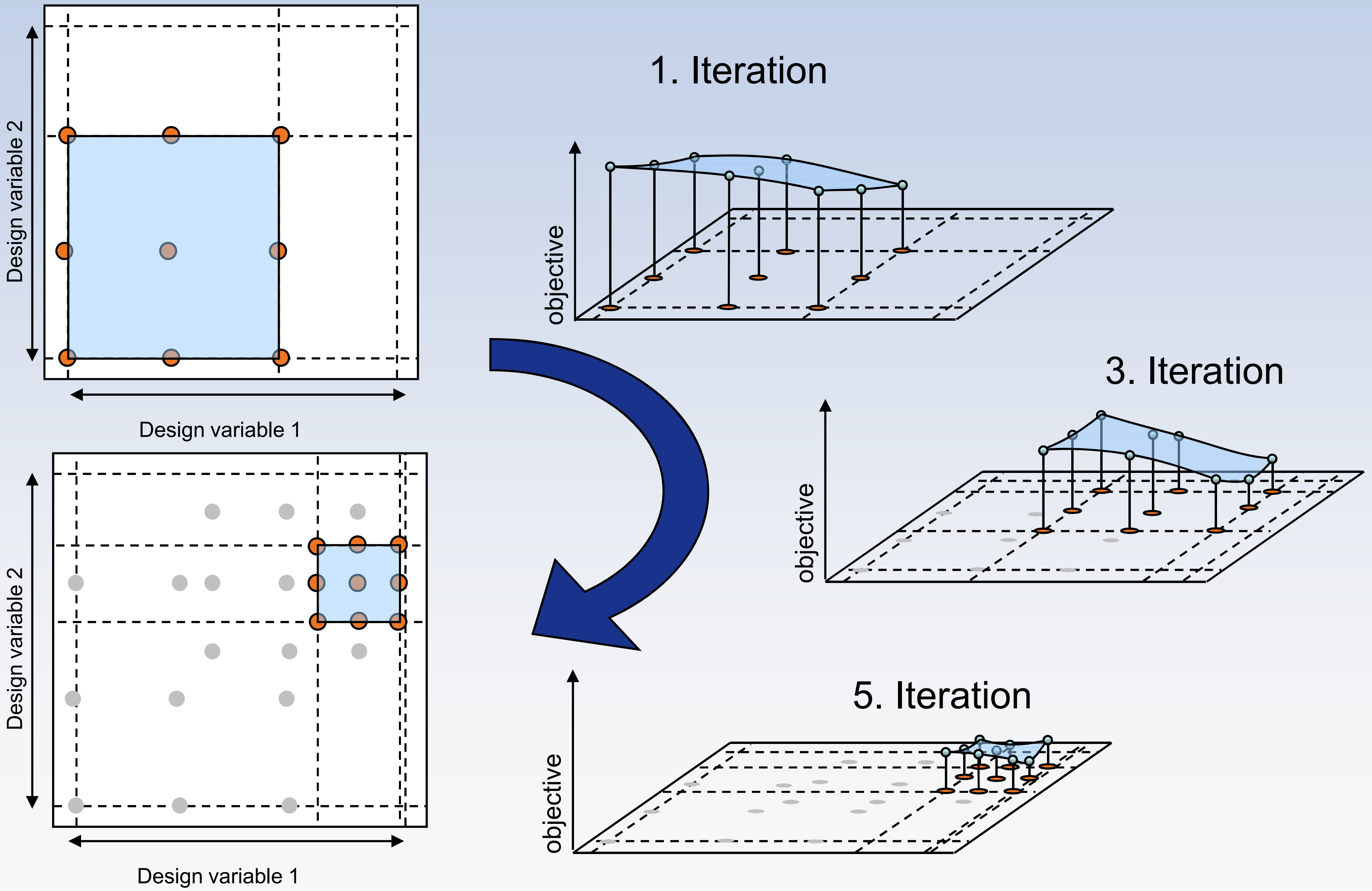


Evolutionary Algorithms (EA)

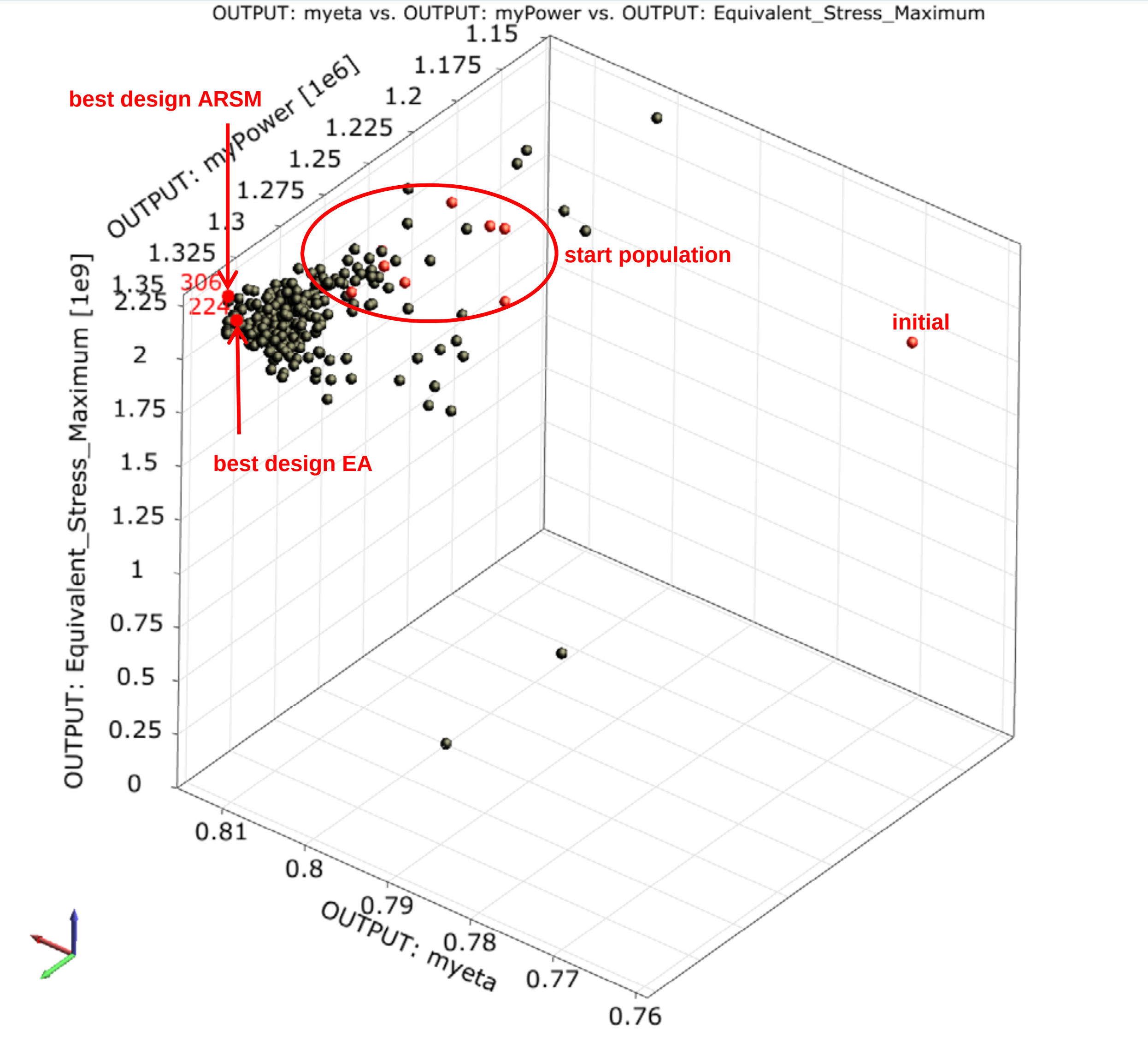


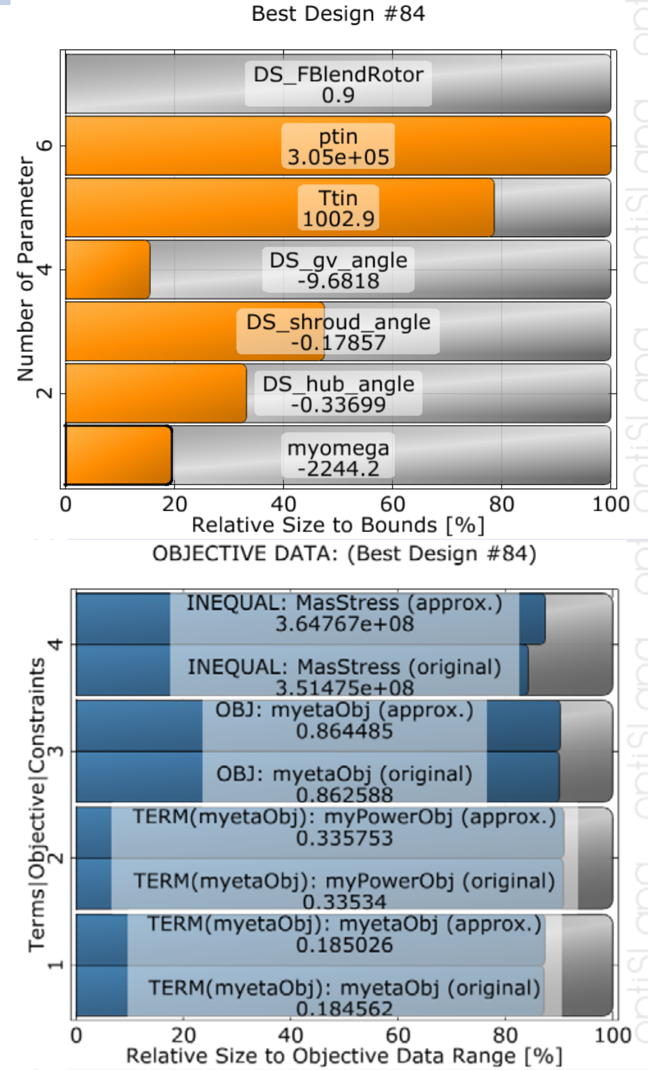
- **Due the non-convex behavior of the efficiency and nonlinear power function a global search strategy using genetic algorithm is recommended**

Adaptive Response Surface Methods (Local)

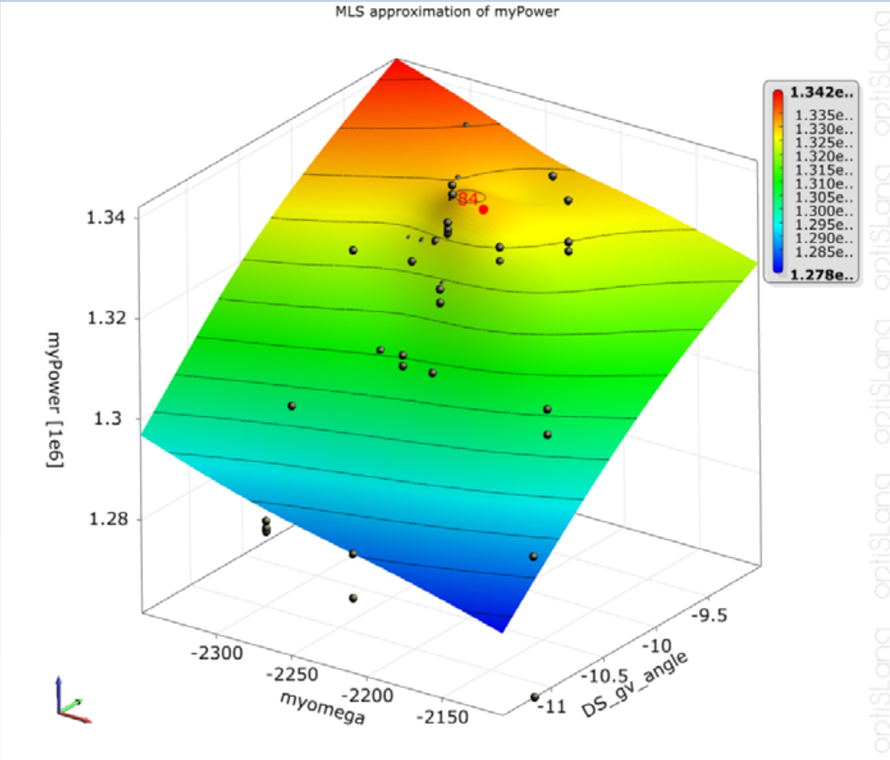


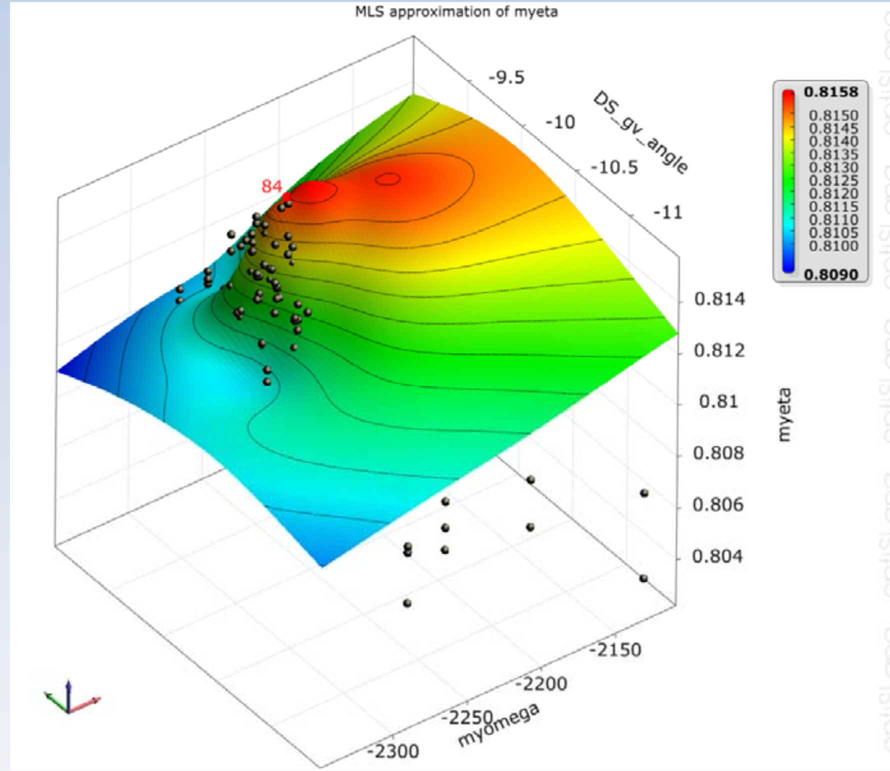
Adaptive Response Surface (ARSM)





Adaptive Response Surface (ARSM)

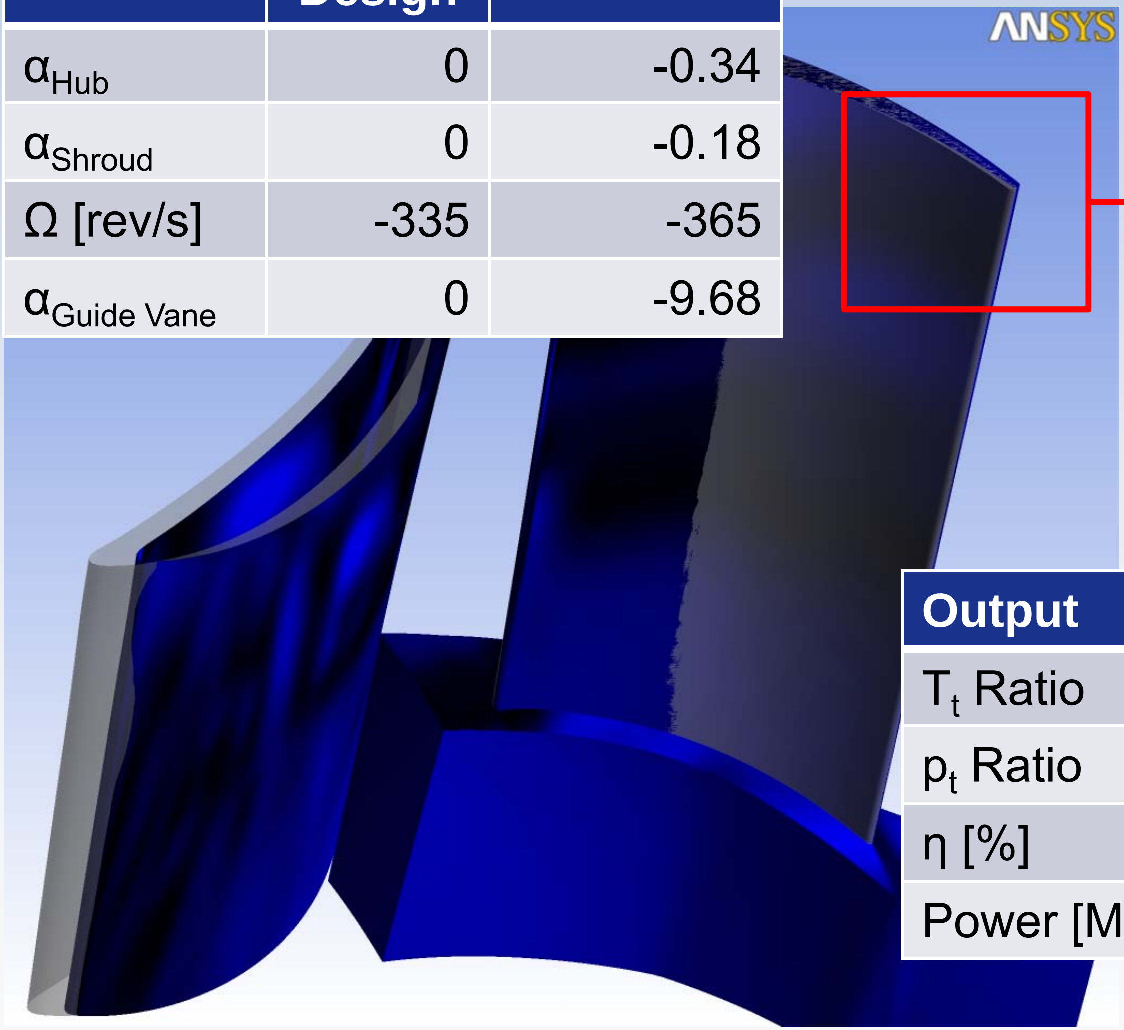


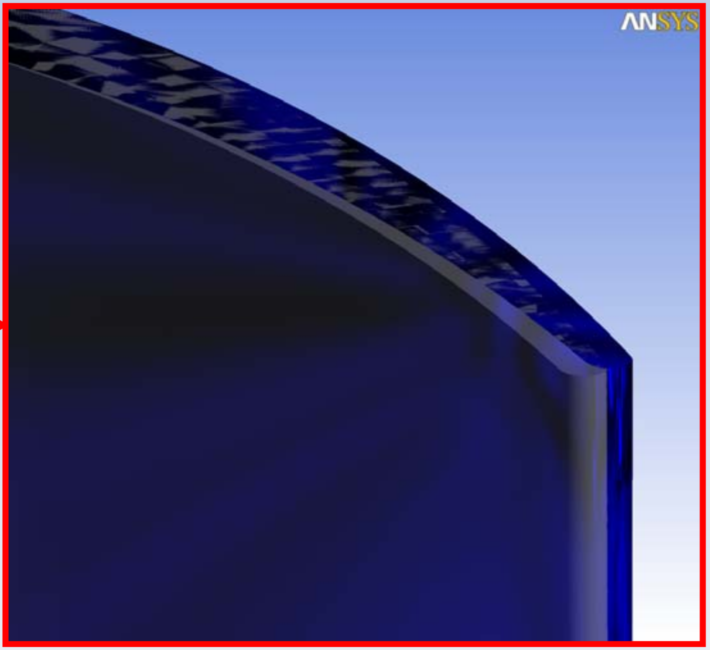


- **The ARSM does not provide differentiable and smooth problems; very efficient for n < 15 design parameters**
- **Starting solution is based on the best design of the EA**
- **The design space is reduced to 20% around start solution**

Initial vs. Optimized Design

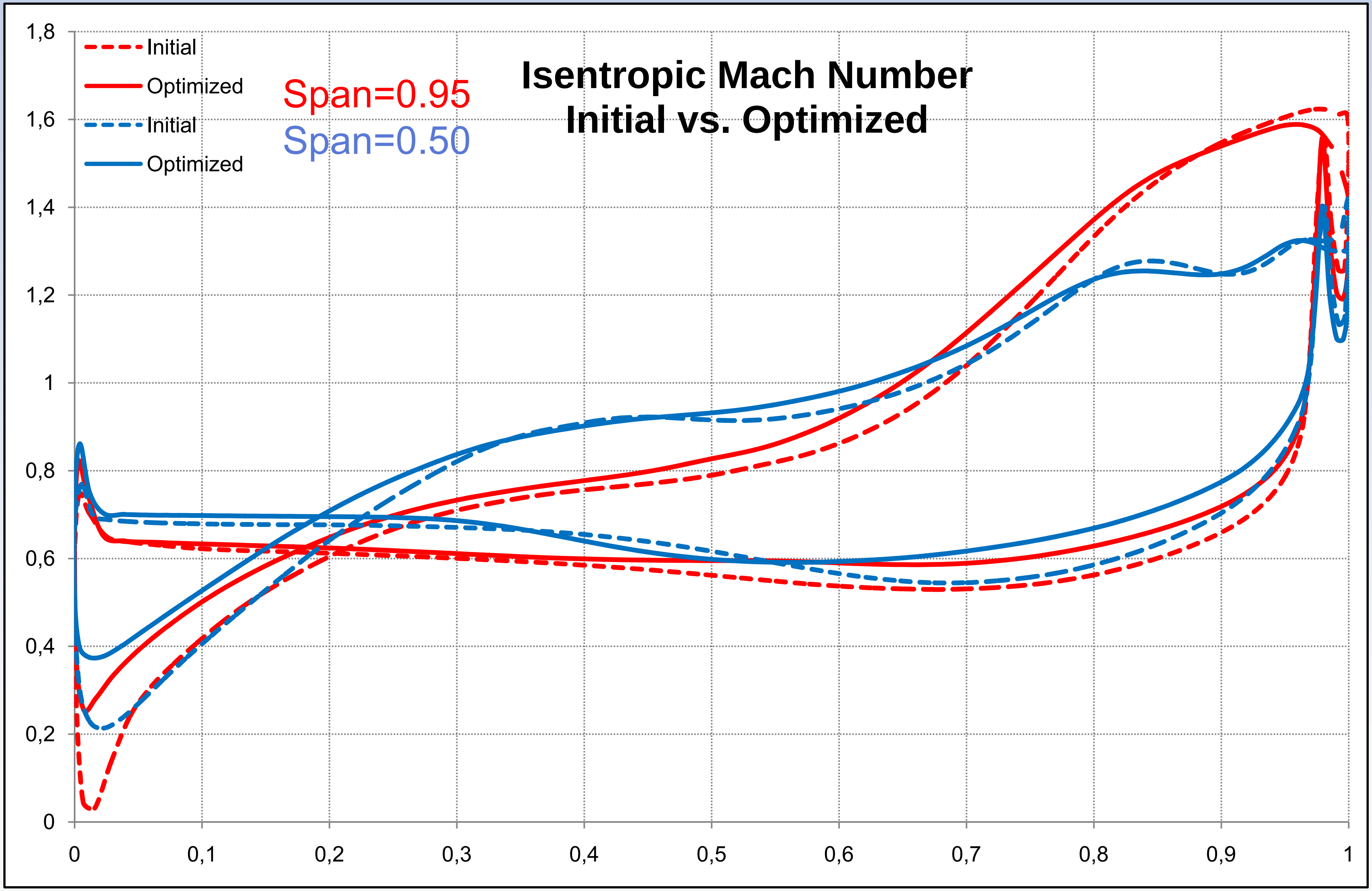
Input	Initial Design	Optimized
α_{Hub}	0	-0.34
α_{Shroud}	0	-0.18
Ω [rev/s]	-335	-365
$\alpha_{Guide\ Vane}$	0	-9.68





Output	Initial Design	Optimized
T_t Ratio	1.116	1.151
p_t Ratio	1.674	1.848
η [%]	71.65	81.54
Power [MW]	1.208	1.329

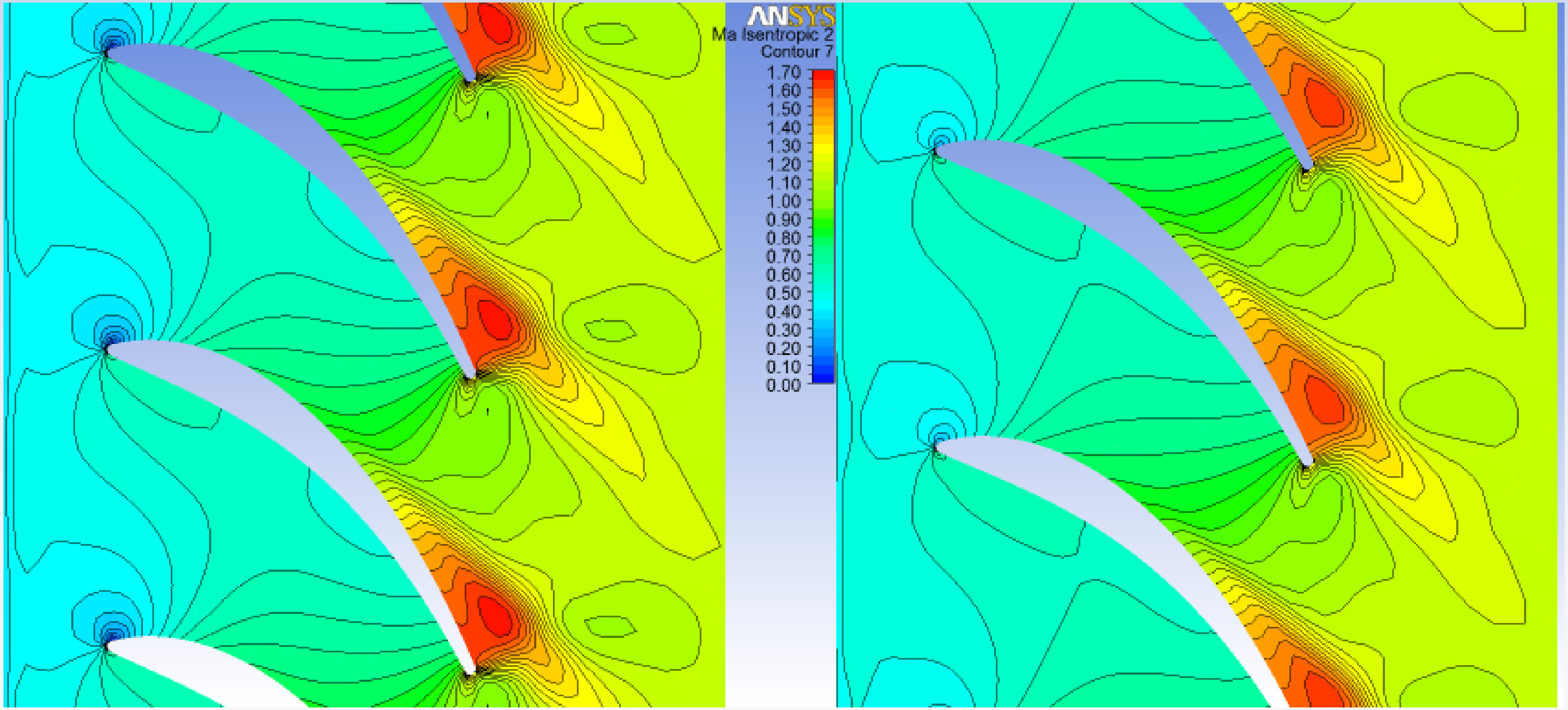
Initial vs. Optimized Design



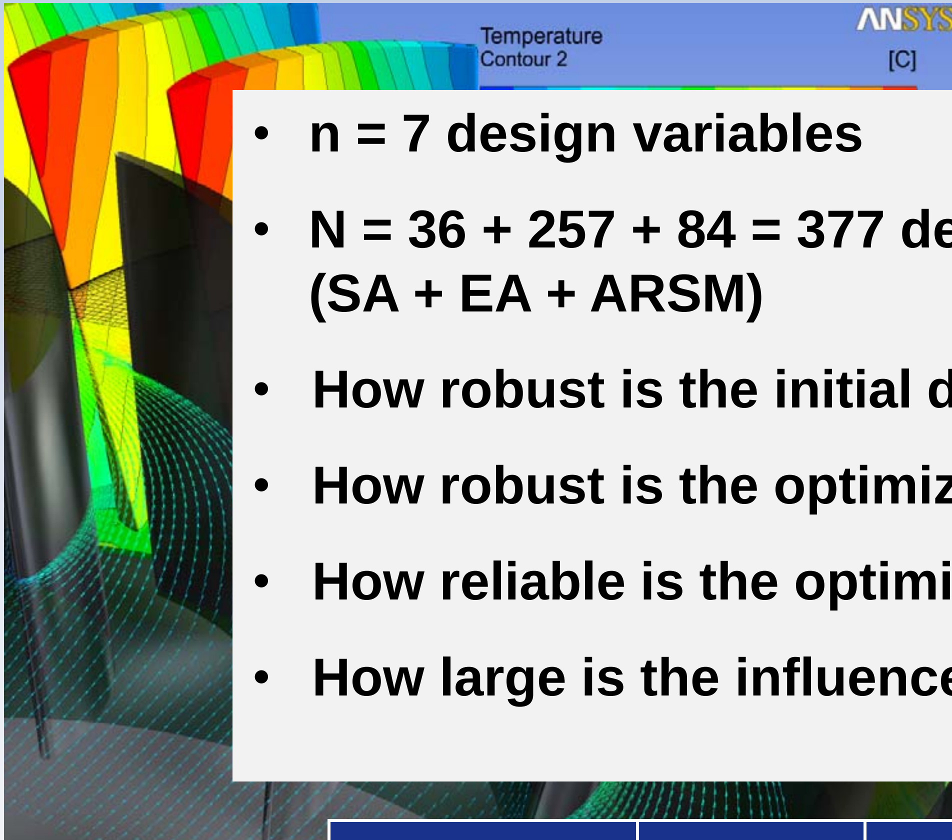
Initial vs. Optimized Design

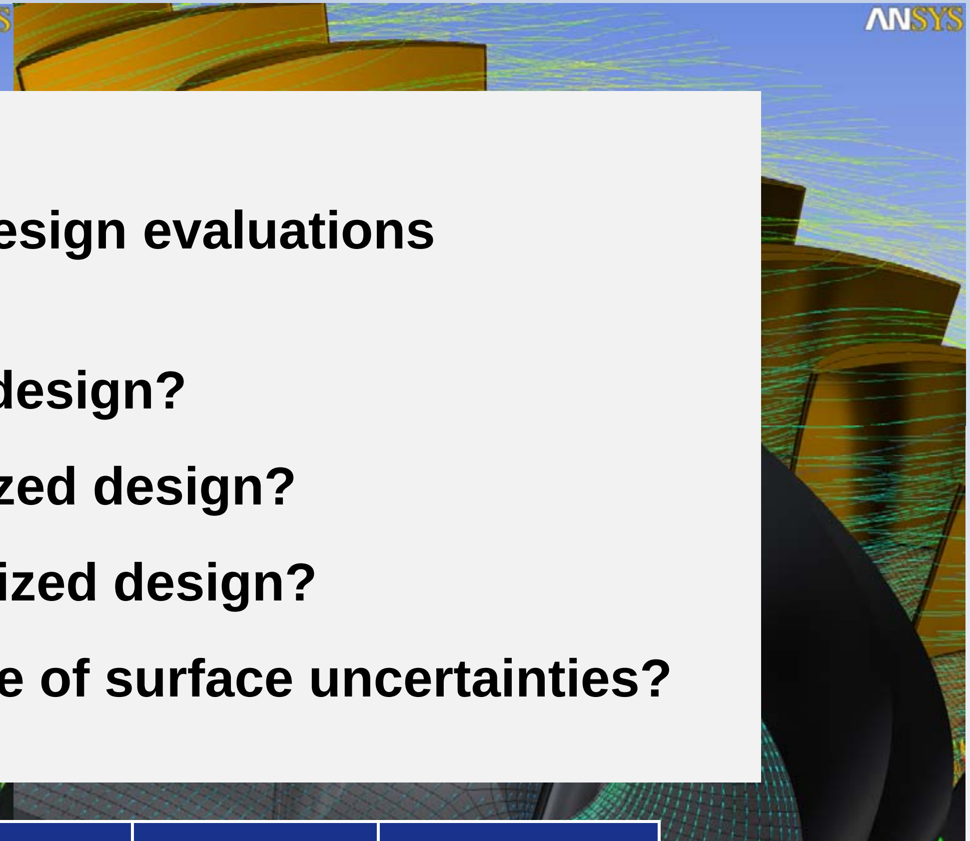
Isotropic Mach Number

Initial | Rotor | Optimized



Initial vs. Optimized Design





- **n = 7 design variables**
- **N = 36 + 257 + 84 = 377 design evaluations (SA + EA + ARSM)**
- **How robust is the initial design?**
- **How robust is the optimized design?**
- **How reliable is the optimized design?**
- **How large is the influence of surface uncertainties?**

Output	Initial	DoE	EA	ARSM
Objective	1.0766	0.90034	0.86841	0.86259
η [%]	71.65	80.60	81.26	81.54
Power [MW]	1.208	1.304	1.343	1.329

Parameterization
Process & Geometry

Design of
Experiments

Design Optimization

Robustness Evaluation

Design for Six Sigma

Robustness Evaluation

- **Identification of non-robustness**
  – Variance of the responses increase
  – Moving of the mean values
  – Responses exceed the limit states
  – Undesired outliers
  – System failures (buckling, resonances, recirculation...)

- **Benefit of robustness evaluation**
  – Correlation between parameters and responses
  – Find most-relevant random parameters to reduce the stochastic problem

Robustness Evaluation

- **Limit state conditions**

Save State Condition

Save State Condition

Name	Function	active
LimitStress	2.8e9-Equivalent_Stress_Maximum	☑
LimitEta	myeta-0.795	☑
LimitPower	myPower-1.0e6	☑

Add Limit State Function | Remove Limit State Function | OK | Cancel

- **Random parameters**

AxialTurbine_04ROBUSTorg.pro

Opti | Robust | Output | Strings | Constraints | Objectives

#	Name	Distribution	Mean	CoV	Std...	L...	...	...	...
1	myomega	Normal	-2094.39	-0.02	41....	–	–	...	☑
2	DS_hub_angle	Normal	0.0	Infinity	0.0...	–	–	...	☑
3	DS_shroud_angle	Normal	0.0	Infinity	0.0...	–	–	...	☑
4	DS_gv_angle	Normal	0.0	Infinity	0.1...	–	–	...	☑
5	Ttin	Normal	1000.0	0.02	20.0	–	–	...	☑
6	ptin	Normal	300000.0	0.03	900...	–	–	...	☑
7	pout	Normal	87000.0	0.02	174...	–	–	...	☑
8	myAirCP	Normal	1004.4	0.03	30....	–	–	...	☑
9	myAirR	Normal	287.102	0.03	8.6...	–	–	...	☑
10	mySteelCP	Normal	434.0	0.05	21....	–	–	...	☑
11	mySteelDensity	Normal	7850.0	0.01	78.5	–	–	...	☑
12	mySteelLambda	Normal	60.5	0.04	2.42	–	–	...	☑
13	DS_FBlendRotor	Normal	1.0	0.02	0.02	–	–	...	☑
14	Youngs_Modulus	Normal	2.0E11	0.03	6.0E9	–	–	...	☑
15	Poissons_Ratio	Normal	0.3	0.1	0.03	–	–	...	☑

Cancel | OK

AxialTurbine_04ROBUST.pro

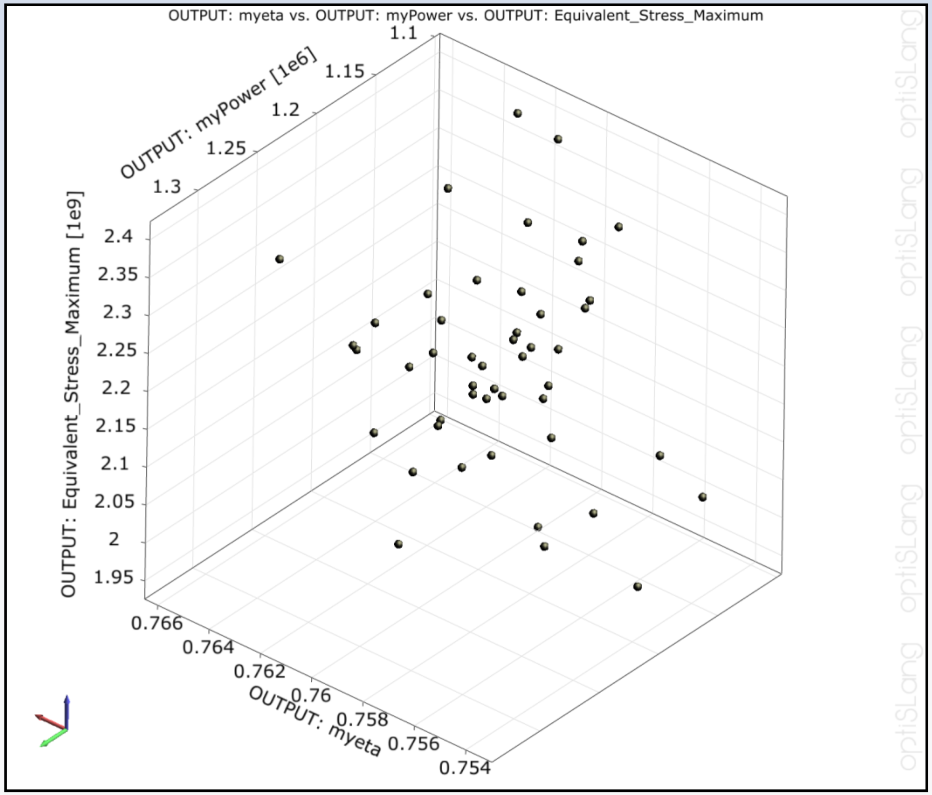
Opti | Robust | Output | Strings | Constraints | Objectives

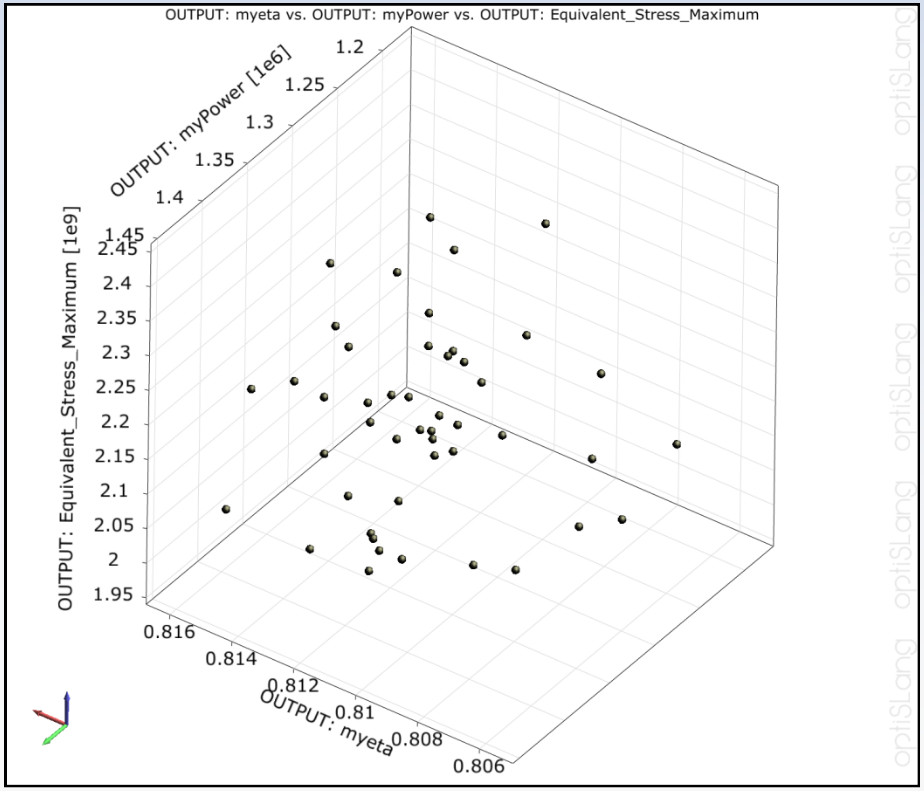
#	Name	Distribution	Mean	CoV	Stddev	Lo...	U...	...	...	...
1	myomega	Normal	-2244.21541...	-0.02	44.88...	–	–	...	☑	☐
2	DS_hub_angle	Normal	-0.33698805...	-0.02	0.006...	–	–	...	☑	☐
3	DS_shroud_angle	Normal	-0.17857451...	-0.02	0.003...	–	–	...	☑	☐
4	DS_gv_angle	Normal	-9.68181702...	-0.02	0.193...	–	–	...	☑	☐
5	Ttin	Normal	1002.859199...	0.02	20.05...	–	–	...	☑	☐
6	ptin	Normal	305000.0	0.03	9150.0	–	–	...	☑	☐
7	pout	Normal	87000.0	0.02	1740.0	–	–	...	☑	☐
8	myAirCP	Normal	1004.4	0.03	30.13...	–	–	...	☑	☐
9	myAirR	Normal	287.102	0.03	8.613...	–	–	...	☑	☐
10	mySteelCP	Normal	434.0	0.05	21.70...	–	–	...	☑	☐
11	mySteelDensity	Normal	7850.0	0.01	78.5	–	–	...	☑	☐
12	mySteelLambda	Normal	60.5	0.04	2.42	–	–	...	☑	☐
13	DS_FBlendRotor	Normal	0.9	0.02	0.018...	–	–	...	☑	☐
14	Youngs_Modulus	Normal	2.0E11	0.03	6.0E9	–	–	...	☑	☐
15	Poissons_Ratio	Normal	0.3	0.1	0.03	–	–	...	☑	☐

Cancel | OK

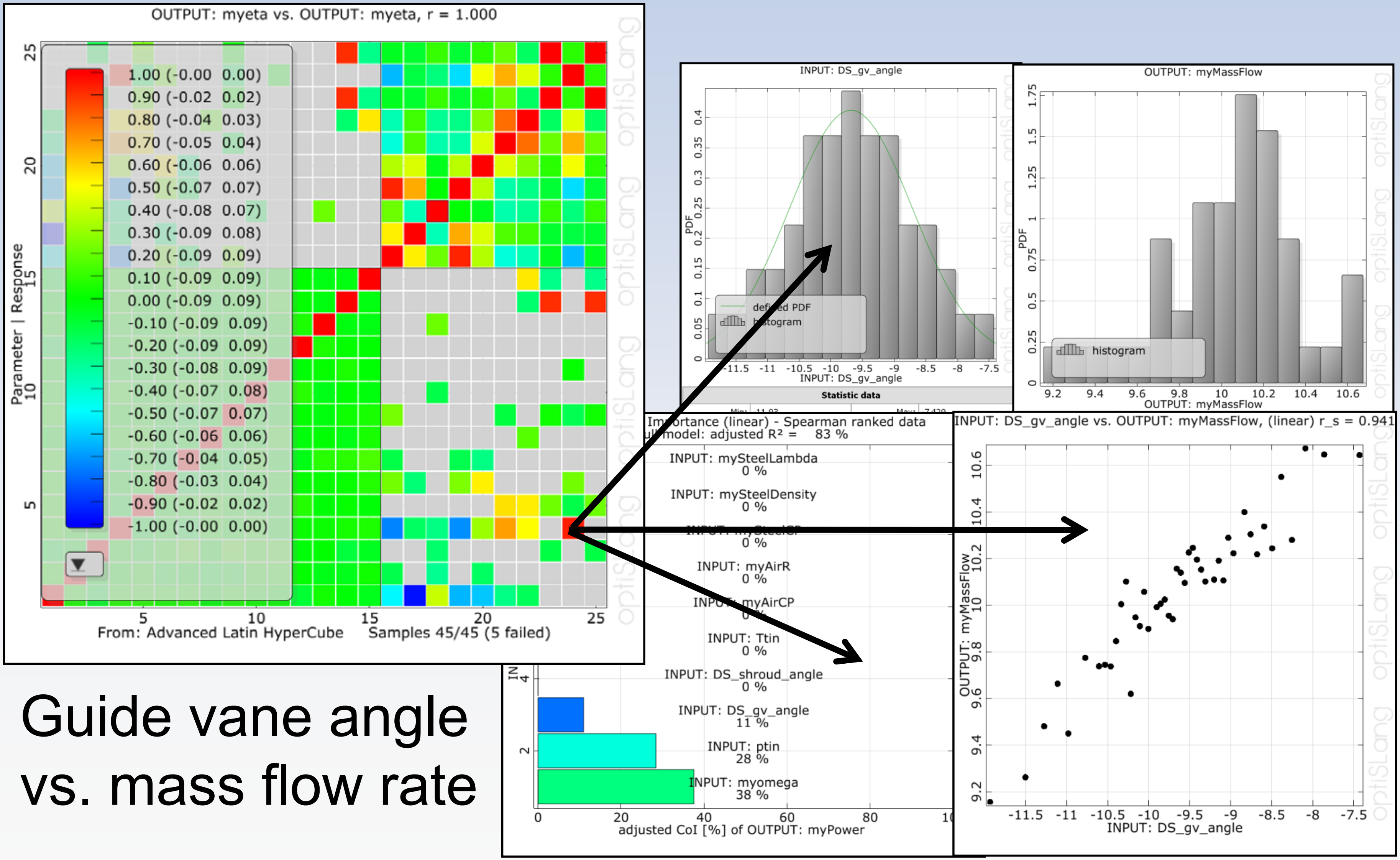
Latin Hypercube

- **n = 15 random parameters**
- **N = 50 design evaluations**
- **Initial vs. optimized design**





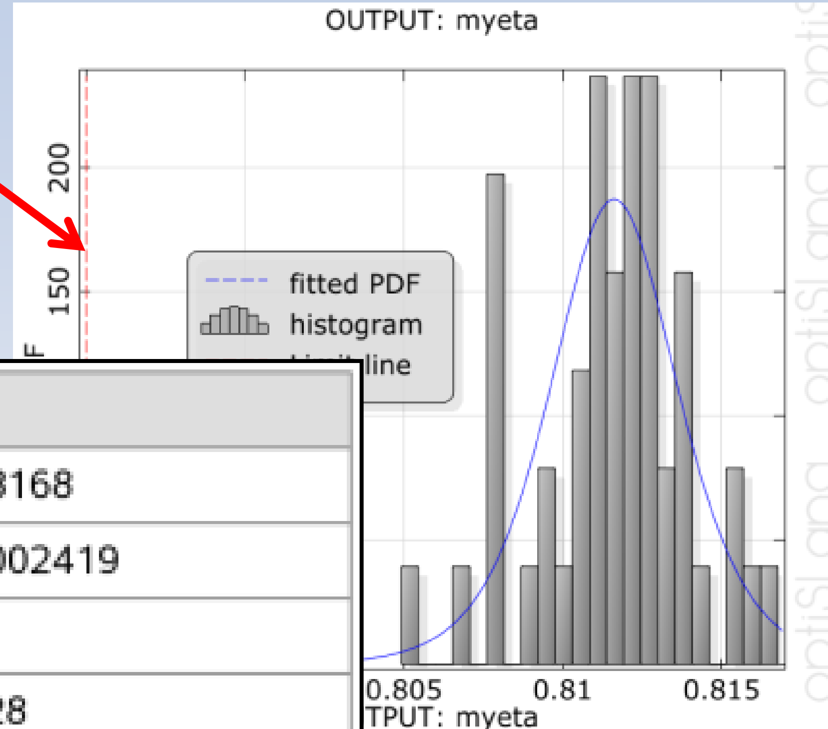
Correlation, CoI, Histogram, Anthill Plot



Guide vane angle vs. mass flow rate

Histograms

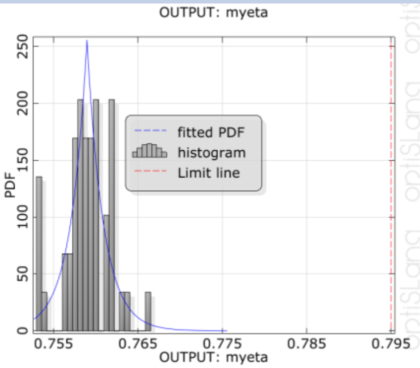
Limit for Result



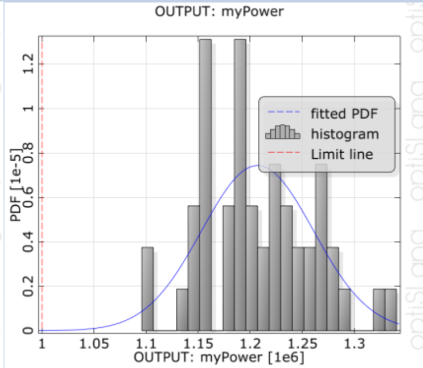
Statistic data			
Min:	0.8049	Max:	0.8168
Mean:	0.8116	Sigma:	0.002419
CV:	0.00298		
Skewness:	-0.4368	Kurtosis:	3.28
Fitted PDF: Logistic			
Mean:	0.8116	Sigma:	0.002419
Limit x = 0.795			
P_rel =	0	P_fit =	3.87374e-06

Statistic data			
		Max:	0.8168
		Sigma:	0.002419
		Kurtosis:	3.28
ed PDF: Logistic			
		Sigma:	0.002419
Limit x = 0.795			
P_rel =	0	P_fit =	3.87374e-06

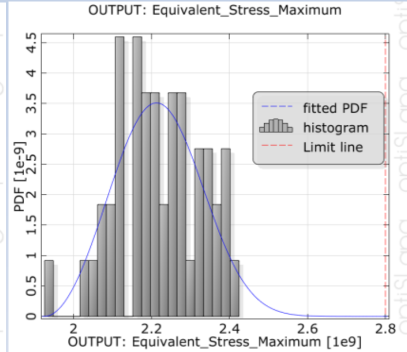
Histograms



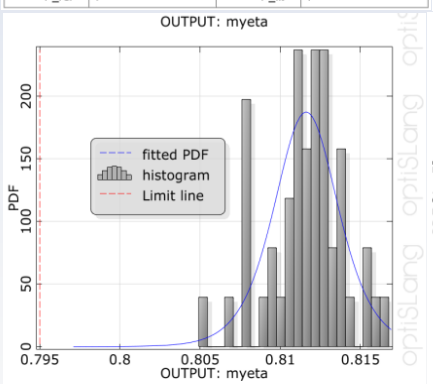
Statistic data			
Min:	0.753	Max:	0.7665
Mean:	0.759	Sigma:	0.002767
CV:	0.003645		
Skewness:	-0.1759	Kurtosis:	3.679
Fitted PDF: Laplace			
Mean:	0.759	Sigma:	0.002767
Limit x = 0.795			
P_rel =	1	P_fit =	1



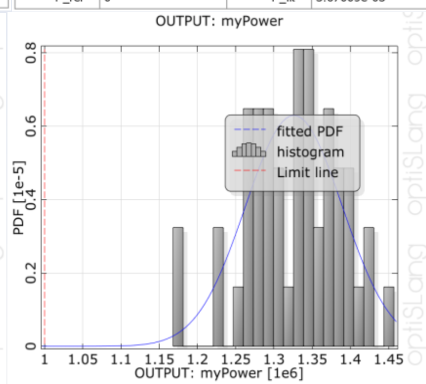
Statistic data			
Min:	1.096e+06	Max:	1.341e+06
Mean:	1.207e+06	Sigma:	5.364e+04
CV:	0.04444		
Skewness:	0.2879	Kurtosis:	2.766
Fitted PDF: Normal			
Mean:	1.207e+06	Sigma:	5.364e+04
Limit x = 1e+06			
P_rel =	0	P_fit =	5.67009e-05



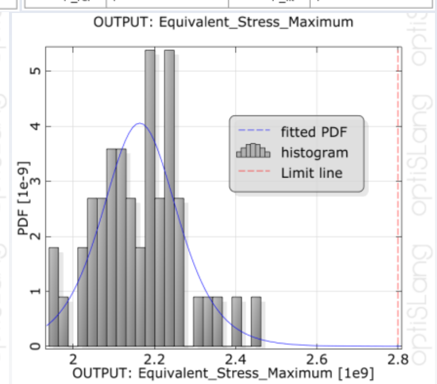
Statistic data			
Min:	1.926e+09	Max:	2.424e+09
Mean:	2.221e+09	Sigma:	1.086e+08
CV:	0.04892		
Skewness:	-0.2418	Kurtosis:	2.725
Fitted PDF: Extreme Typ III (Max) Weibull			
Mean:	2.221e+09	Sigma:	1.086e+08
Lower cut:	1.926e+09		
Limit x = 2.8e+09			
P_rel =	1	P_fit =	1



Statistic data			
Min:	0.8049	Max:	0.8168
Mean:	0.8116	Sigma:	0.002419
CV:	0.00298		
Skewness:	-0.4368	Kurtosis:	3.28
Fitted PDF: Logistic			
Mean:	0.8116	Sigma:	0.002419
Limit x = 0.795			
P_rel =	0	P_fit =	3.87374e-06



Statistic data			
Min:	1.168e+06	Max:	1.457e+06
Mean:	1.326e+06	Sigma:	6.335e+04
CV:	0.04776		
Skewness:	-0.3664	Kurtosis:	2.825
Fitted PDF: Normal			
Mean:	1.326e+06	Sigma:	6.335e+04
Limit x = 1e+06			
P_rel =	0	P_fit =	1.3062e-07

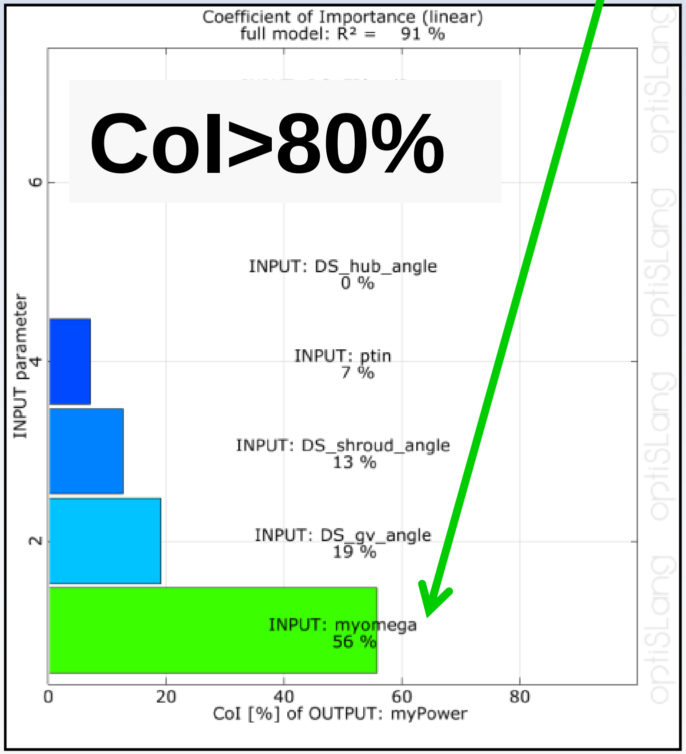


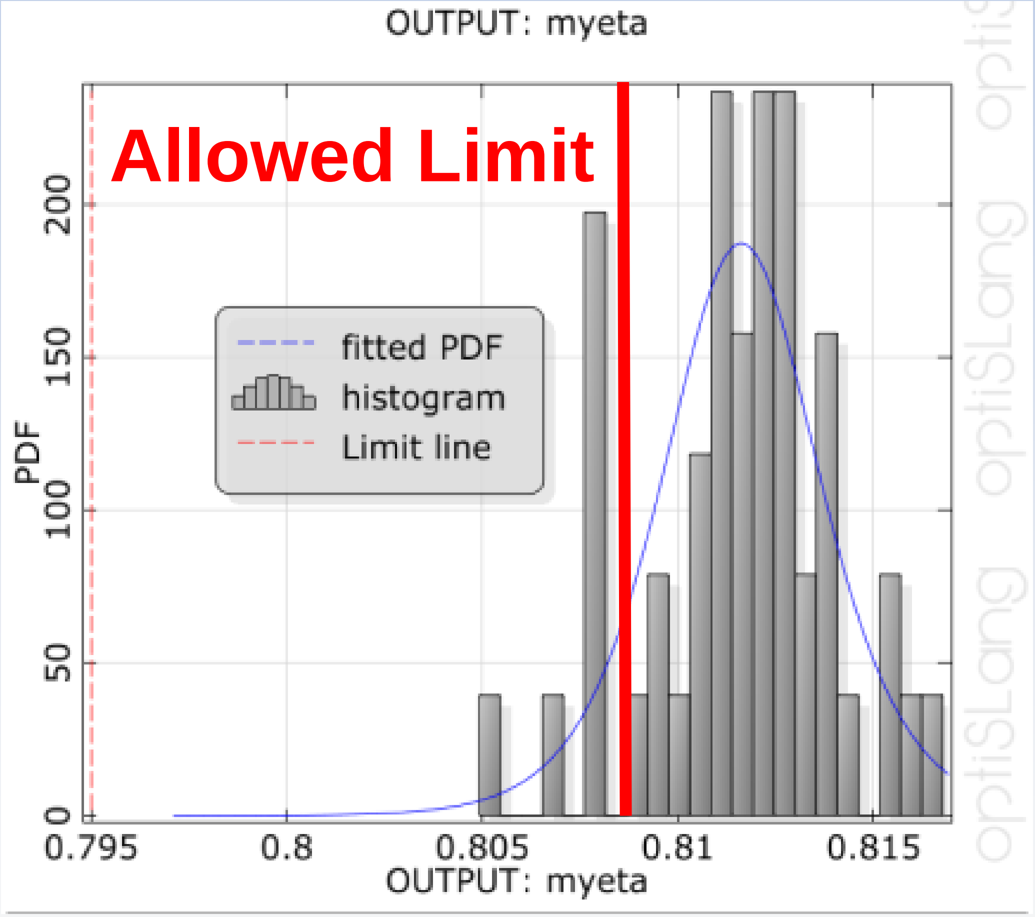
Statistic data			
Min:	1.94e+09	Max:	2.462e+09
Mean:	2.164e+09	Sigma:	1.118e+08
CV:	0.05165		
Skewness:	0.3229	Kurtosis:	3.244
Fitted PDF: Logistic			
Mean:	2.164e+09	Sigma:	1.118e+08
Limit x = 2.8e+09			
P_rel =	1	P_fit =	0.999967

- **Non-robust initial design**
- **Robust design up to a sigma level of 4.5**

Conclusion Robustness

- **Is there a problem?**
- **Can we explain, CoI?**
- **Who is responsible?**





Parameterization
Process & Geometry

Sensitivity Analysis

Design Optimization

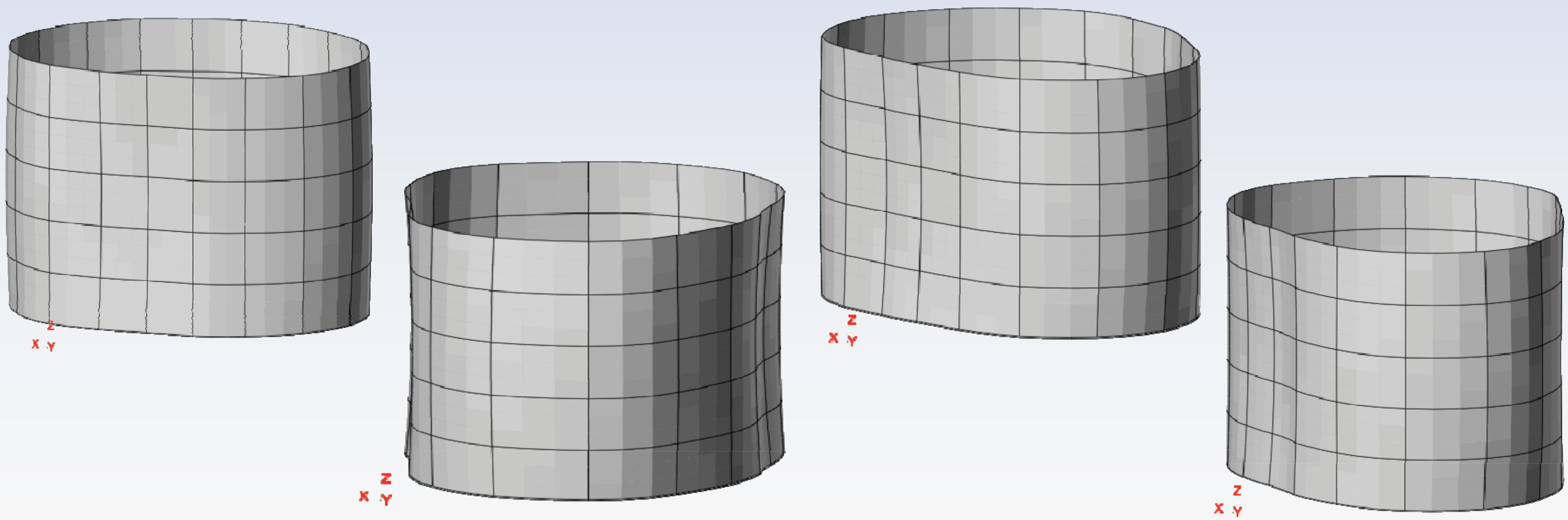
Random Fields

Design for Six Sigma

Random Fields: Background

What is a Random Field?

- **Random variation of a property (geometry, material, load, ...) over space.**
- **Spatial domain defined by the observed structure.**
- **A property takes random values at each point on the structure. Values at different locations may be correlated.**



(Example: random realizations of a cylinder)

Random Fields: Background

Data sources for random field modelling:

- **Measurements at discrete points (e.g. geometry scan),**
- **Simulation (e.g. of a manufacturing process with random parameters)**

Random field discretization:

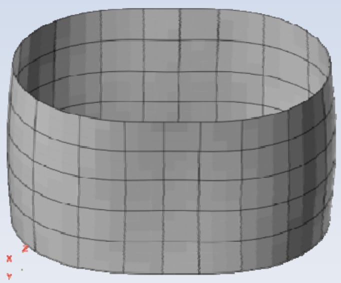
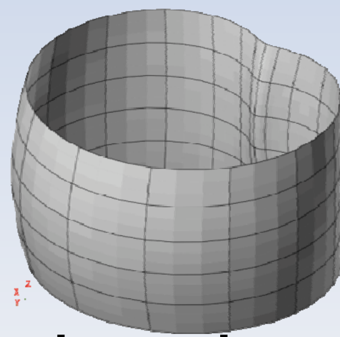
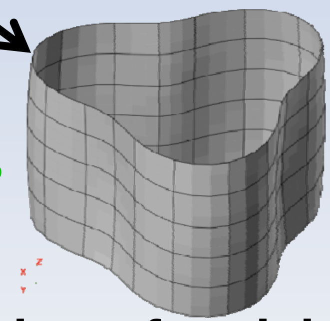
- **Nodes (e.g. imperfect coordinates,…)**
- **Elements (e.g. material, initial strains,…)**

- **By discretization, the random field is defined by:**
- **Mean values vector and**
- **Standard deviations vector and correlation matrix, or**
- **Covariance matrix**

Random Fields: Background

Random field simulation:

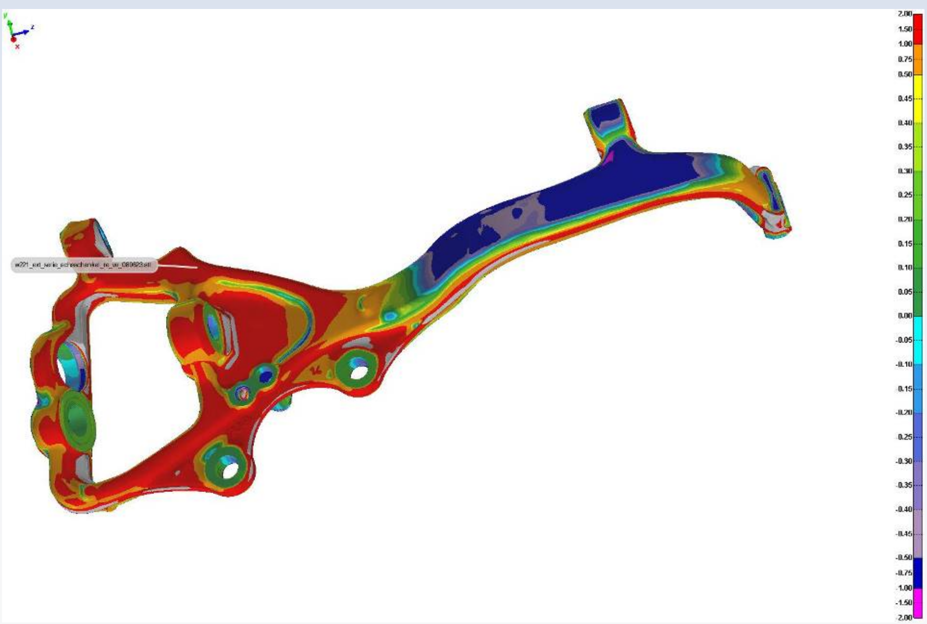
- **After decomposition of the covariance matrix, the random field is expanded as a series of random amplitudes and deterministic shape functions.**

$X = Y_1$  $+\ Y_2$  $+\ Y_3$  $+\ \ldots$

- **The series may be truncated to reduce the number of variables,**
- **Quality of truncated series is measured by the variability fraction**
- **Post-Processing of shape functions corresponding to most relevant random variables (in Robustness Analysis) gives insight to manufacturing tolerances.**

Measure Spatial Deviations

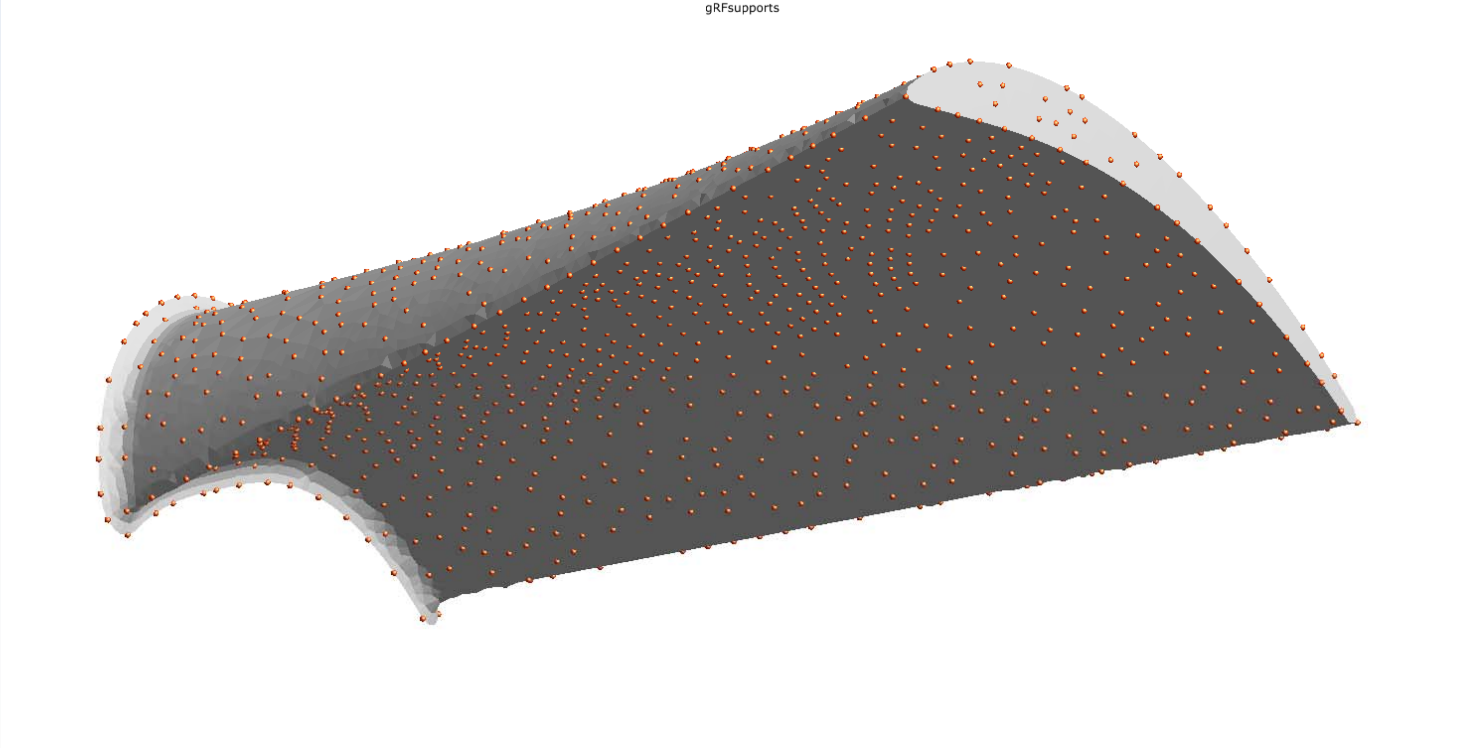
Example:
- Using 3D digitizer
- Based on the principle of triangulation, projected fringe patterns are observed with cameras, 3D coordinates for each camera pixel are calculated, a polygon mesh of the object’s surface is generated
- Deviations from CAD geometry can be calculated



Example: Axial Turbine Blade

Scope of analysis:

- **Given is the FE model of a turbine blade**
- **Imperfect geometry is scanned at 1500 points on the surface**
- **A Random Field is modelled by the statistics of measurements**
- **Random realizations of the turbine blade are generated by optiSLang and put into CFD analysis with ANSYS workbench**

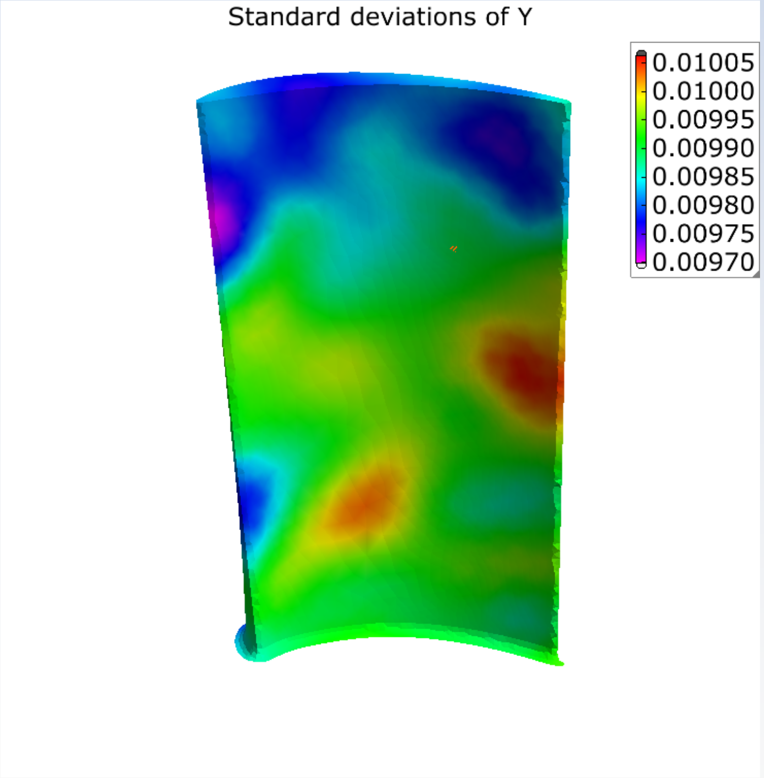


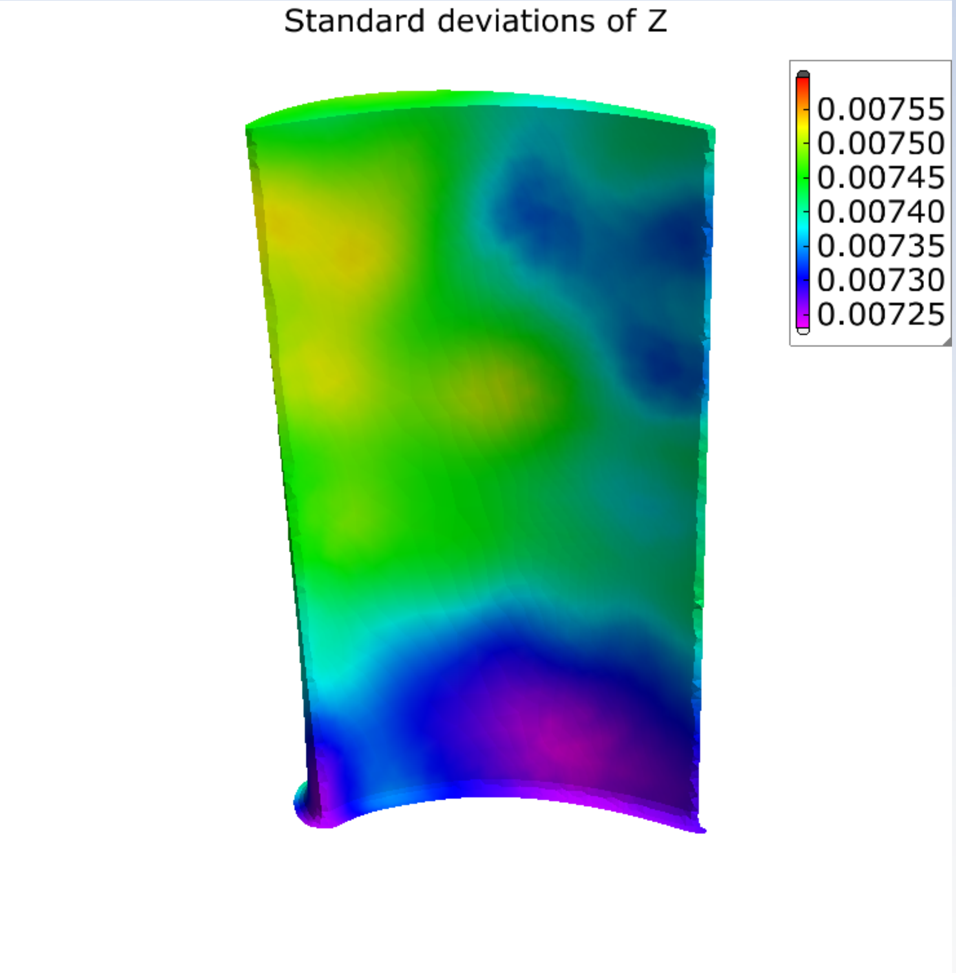
(Measurement points on blade surface)

Example: Axial Turbine Blade

Measurements:

- **Geometry can be scanned on the surface of the blade**
- **Here, measures in y- and z-direction are taken (x: longitudinal direction)**
- **Mean values of imperfections are assumed zero**



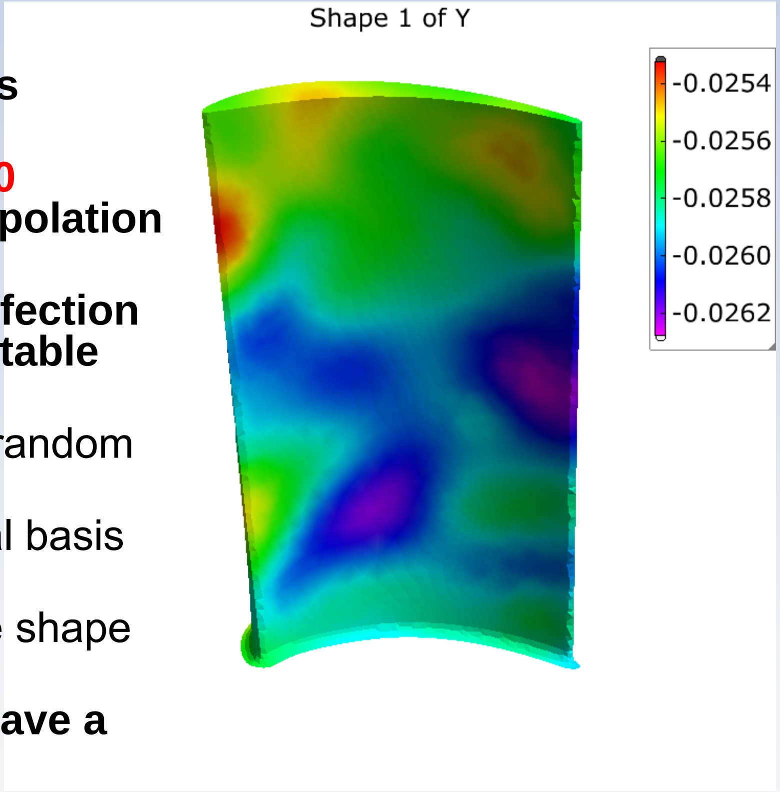


(Standard deviations of measured imperfections)

Example: Axial Turbine Blade

Random Field discretization:

- **Number of imperfection modes depends on number of DOF**
- **Can be reduced using the 1500 measurement points and interpolation of the finite element mesh**
- **Further reduction of the imperfection shape number using an acceptable variability of modal basis:**
  - Normed variability of total random field data = 9.7748e-05
  - Normed variability of modal basis (n=18) = 9.7748e-05
  - Normed variability of mode shape #1 = 9.7672e-05
- **Question: which parameters have a significant influence of the performance relevant output parameters?**



Object: AMPLITUDES_Y
Object info: 2 2 9 1 0

0.38276414138812
0.007496567990285
0.0051987752213625
0.003323636789174
0.0027613964023576
0.0019991977189793
0.0018763653566348
0.001647552369793
0.0013368316745761

Object: AMPLITUDES_Z
Object info: 2 2 9 1 0

0.28708343060908
0.0054186311280151
0.0036936006781938
0.002228785060336
0.0019874267604701
0.0015294461571268
0.0014213940470741
0.0010411406423311
0.00092089226898308

Example: Axial Turbine Blade

AxialTurbine_08ROBUST.pro

Opti | Robust | Output | Strings | Constraints | Objectives

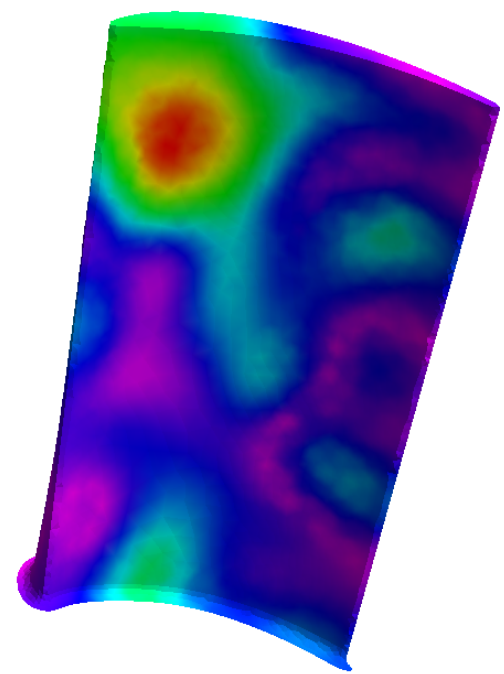
#	Name	Distribution	Mean	CoV	Stddev	Lower Cut	Upper Cut	Format	Ac...	Co...
1	AMP_Y_1	Normal	0.0	Infinity	0.38276414...	-	-	%20.14g	☑	☐
2	AMP_Y_2	Normal	0.0	Infinity	0.00749656...	-	-	%20.14g	☑	☐
3	AMP_Y_3	Normal	0.0	Infinity	0.00519877...	-	-	%20.14g	☑	☐
4	AMP_Y_4	Normal	0.0	Infinity	0.00332363...	-	-	%20.14g	☑	☐
5	AMP_Y_5	Normal	0.0	Infinity	0.00276139...	-	-	%20.14g	☑	☐
6	AMP_Y_6	Normal	0.0	Infinity	0.00199919...	-	-	%20.14g	☑	☐
7	AMP_Y_7	Normal	0.0	Infinity	0.00187636...	-	-	%20.14g	☑	☐
8	AMP_Y_8	Normal	0.0	Infinity	0.00164755...	-	-	%20.14g	☑	☐
9	AMP_Y_9	Normal	0.0	Infinity	0.00133683...	-	-	%20.14g	☑	☐
10	AMP_Z_1	Normal	0.0	Infinity	0.28708343...	-	-	%20.14g	☑	☐
11	AMP_Z_2	Normal	0.0	Infinity	0.00541863...	-	-	%20.14g	☑	☐
12	AMP_Z_3	Normal	0.0	Infinity	0.00369360...	-	-	%20.14g	☑	☐
13	AMP_Z_4	Normal	0.0	Infinity	0.00222878...	-	-	%20.14g	☑	☐
14	AMP_Z_5	Normal	0.0	Infinity	0.00198742...	-	-	%20.14g	☑	☐
15	AMP_Z_6	Normal	0.0	Infinity	0.00152944...	-	-	%20.14g	☑	☐
16	AMP_Z_7	Normal	0.0	Infinity	0.00142139...	-	-	%20.14g	☑	☐
17	AMP_Z_8	Normal	0.0	Infinity	0.00104114...	-	-	%20.14g	☑	☐
18	AMP_Z_9	Normal	0.0	Infinity	9.20892268...	-	-	%20.14g	☑	☐
19	myomega	Normal	-2244.21541...	-0.02	44.8843082...	-	-	%20.14f	☑	☐
20	DS_hub_angle	Normal	-0.33698805...	-0.02	0.00673976...	-	-	%20.14f	☑	☐
21	DS_shroud_angle	Normal	-0.17857451...	-0.02	0.00357149...	-	-	%20.14f	☑	☐
22	DS_gv_angle	Normal	-9.68181702...	-0.02	0.19363634...	-	-	%20.14f	☑	☐
23	Ttin	Normal	1002.85919...	0.02	20.057184	-	-	%20.14f	☑	☐
24	ptin	Normal	305000.0	0.03	9150.0	-	-	%20.14f	☑	☐
25	pout	Normal	87000.0	0.02	1740.0	-	-	%20.14f	☑	☐
26	myAirCP	Normal	1004.4	0.03	30.1319999...	-	-	%20.14f	☑	☐
27	myAirR	Normal	287.102	0.03	8.61305999...	-	-	%20.14f	☑	☐
28	mySteelCP	Normal	434.0	0.05	21.7000000...	-	-	%20.14f	☑	☐
29	mySteelDensity	Normal	7850.0	0.01	78.5	-	-	%20.14f	☑	☐
30	mySteelLambda	Normal	60.5	0.04	2.42	-	-	%20.14f	☑	☐
31	DS_FBlendRotor	Normal	0.9	0.02	0.01800000...	-	-	%20.14f	☑	☐
32	Youngs_Modulus	Normal	2.0E11	0.03	6.0E9	-	-	%20.14f	☑	☐
33	Poissons_Ratio	Normal	0.3	0.1	0.03	-	-	%20.14f	☑	☐

Cancel | OK

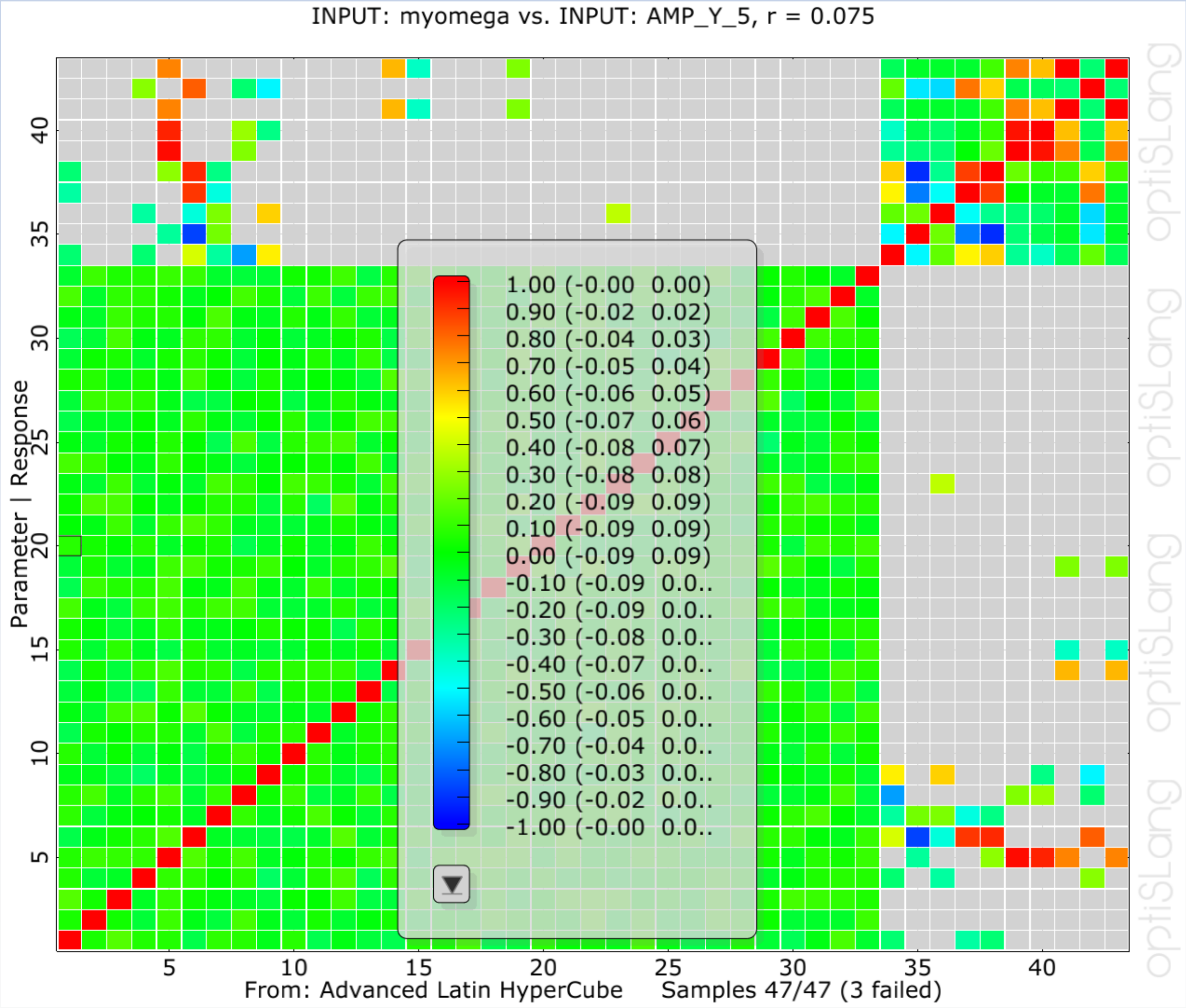
Robsutness Analysis:

- **Including all random variables (n=14) and relevant imperfection modes (n=18)**
- **Possibility of failed designs**
- **Advanced optimized latin hypercube sampling**
- **N = 47**

Norm of Realization



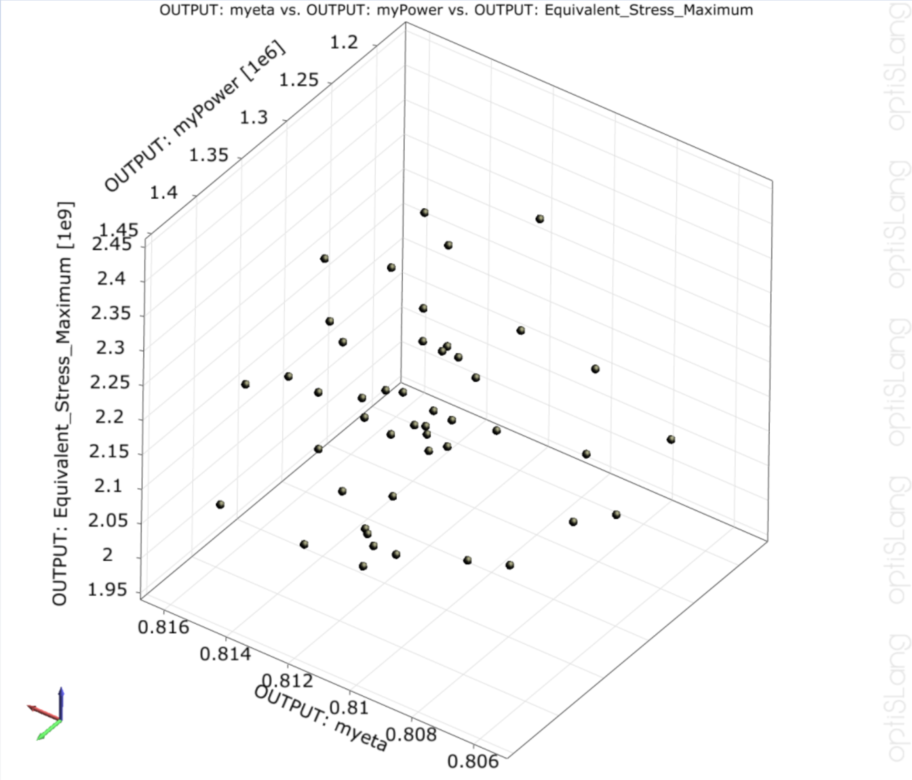
Example: Axial Turbine Blade



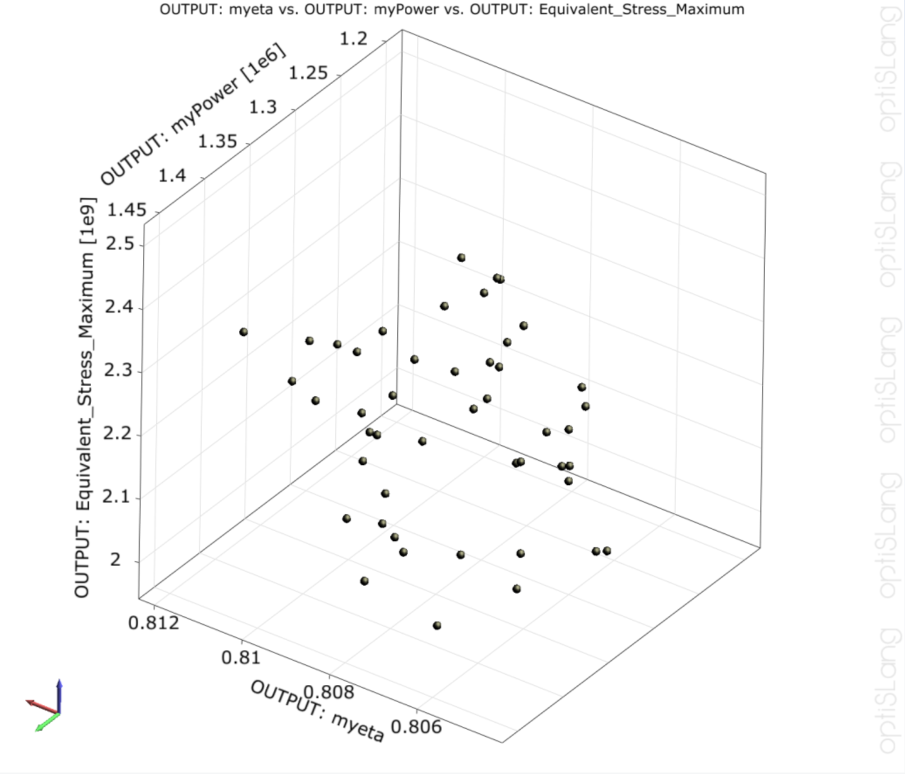
Example: Axial Turbine Blade

Robsutness Analysis:

- **Including all random variables (n=14) and relevant imperfection modes (n=18)**
- **Smaller values for „myeta“**
- **Nearly the same variance of the responses**

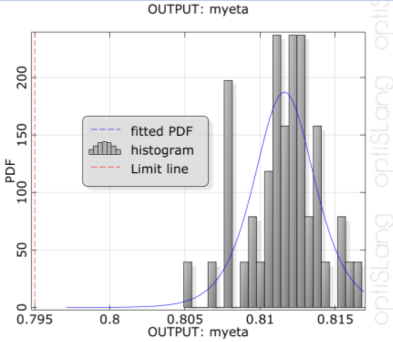


Only random geometry parameters

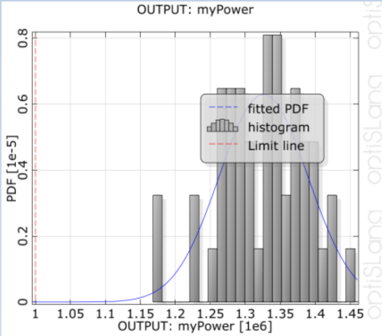


Including the manufactoring tolerances

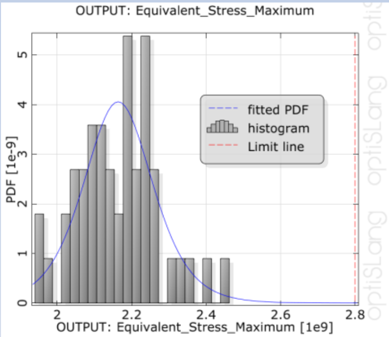
Example: Axial Turbine Blade



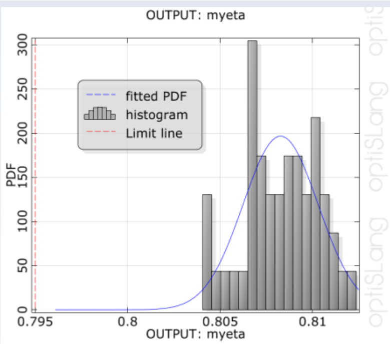
Statistic data			
Min:	0.8049	Max:	0.8168
Mean:	0.8116	Sigma:	0.002419
CV:	0.00298		
Skewness:	-0.4368	Kurtosis:	3.28
Fitted PDF: Logistic			
Mean:	0.8116	Sigma:	0.002419
Limit x = 0.795			
P_rel =	0	P_fit =	3.87374e-06



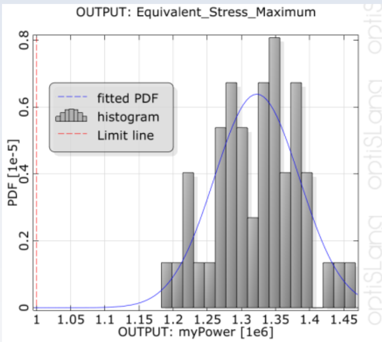
Statistic data			
Min:	1.168e+06	Max:	1.457e+06
Mean:	1.326e+06	Sigma:	6.335e+04
CV:	0.04776		
Skewness:	-0.3664	Kurtosis:	2.825
Fitted PDF: Normal			
Mean:	1.326e+06	Sigma:	6.335e+04
Limit x = 1e+06			
P_rel =	0	P_fit =	1.3062e-07



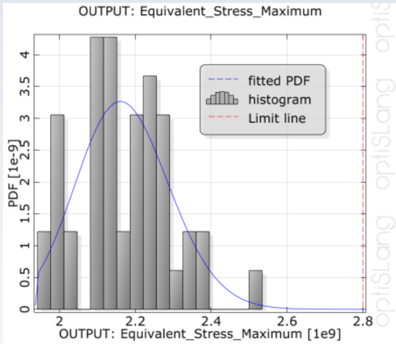
Statistic data			
Min:	1.94e+09	Max:	2.462e+09
Mean:	2.164e+09	Sigma:	1.118e+08
CV:	0.05165		
Skewness:	0.3229	Kurtosis:	3.244
Fitted PDF: Logistic			
Mean:	2.164e+09	Sigma:	1.118e+08
Limit x = 2.8e+09			
P_rel =	1	P_fit =	0.999967



Statistic data			
Min:	0.8041	Max:	0.8124
Mean:	0.8083	Sigma:	0.002028
CV:	0.002509		
Skewness:	-0.1842	Kurtosis:	2.345
Fitted PDF: Normal			
Mean:	0.8083	Sigma:	0.002028
Limit x = 0.795			
P_rel =	0	P_fit =	3.07755e-011
Probability P(X<x) = 0.95			
x_rel =	0.811073	x_fit =	0.811601



Statistic data			
Min:	1.183e+006	Max:	1.467e+006
Mean:	1.323e+006	Sigma:	6.246e+004
CV:	0.04722		
Skewness:	-0.03409	Kurtosis:	2.646
Fitted PDF: Normal			
Mean:	1.323e+006	Sigma:	6.246e+004
Limit x = 1e+006			
P_rel =	0	P_fit =	1.19045e-007
Probability P(X<x) = 0.95			
x_rel =	1.43062e+006	x_fit =	1.42543e+006

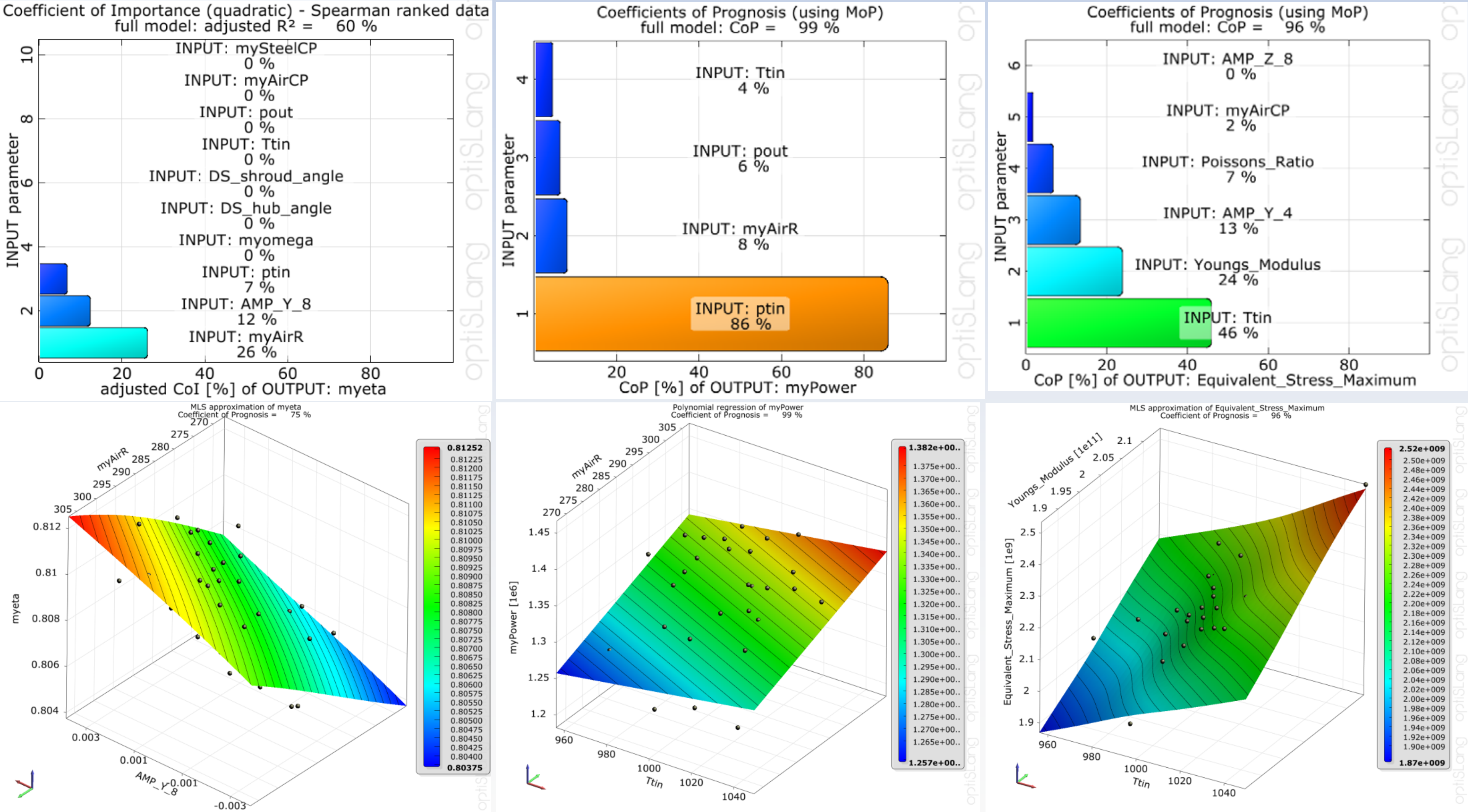


Statistic data			
Min:	1.942e+009	Max:	2.535e+009
Mean:	2.171e+009	Sigma:	1.227e+008
CV:	0.0565		
Skewness:	0.3893	Kurtosis:	3.235
Fitted PDF: Log-Normal			
Mean:	2.171e+009	Sigma:	1.227e+008
Limit x = 2.8e+009			
P_rel =	1	P_fit =	0.999997
Probability P(X<x) = 0.95			
x_rel =	2.37151e+009	x_fit =	2.37861e+009

- **Histograms resulting the random CAD parameters**
- **Robust design up to a sigma level of 4.5**
- **including the manufactoring tolerances**

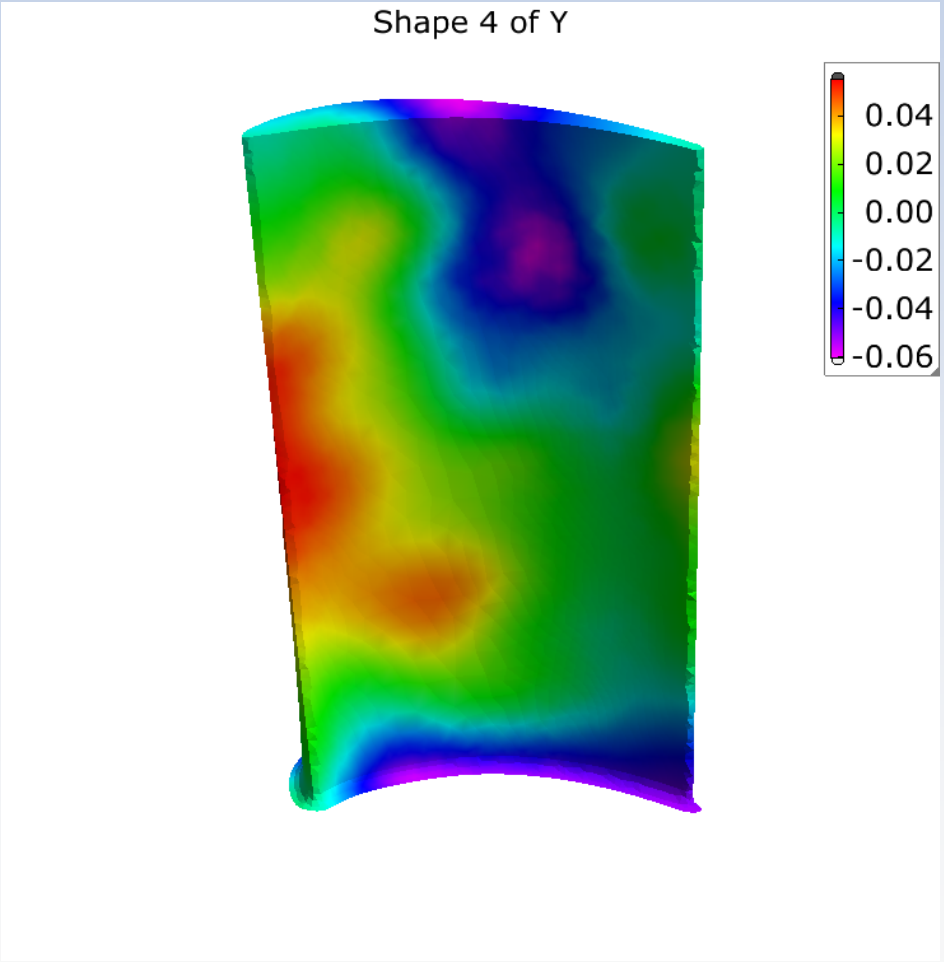
Example: Axial Turbine Blade

Meta-model of optimal and coefficient of prognosis :

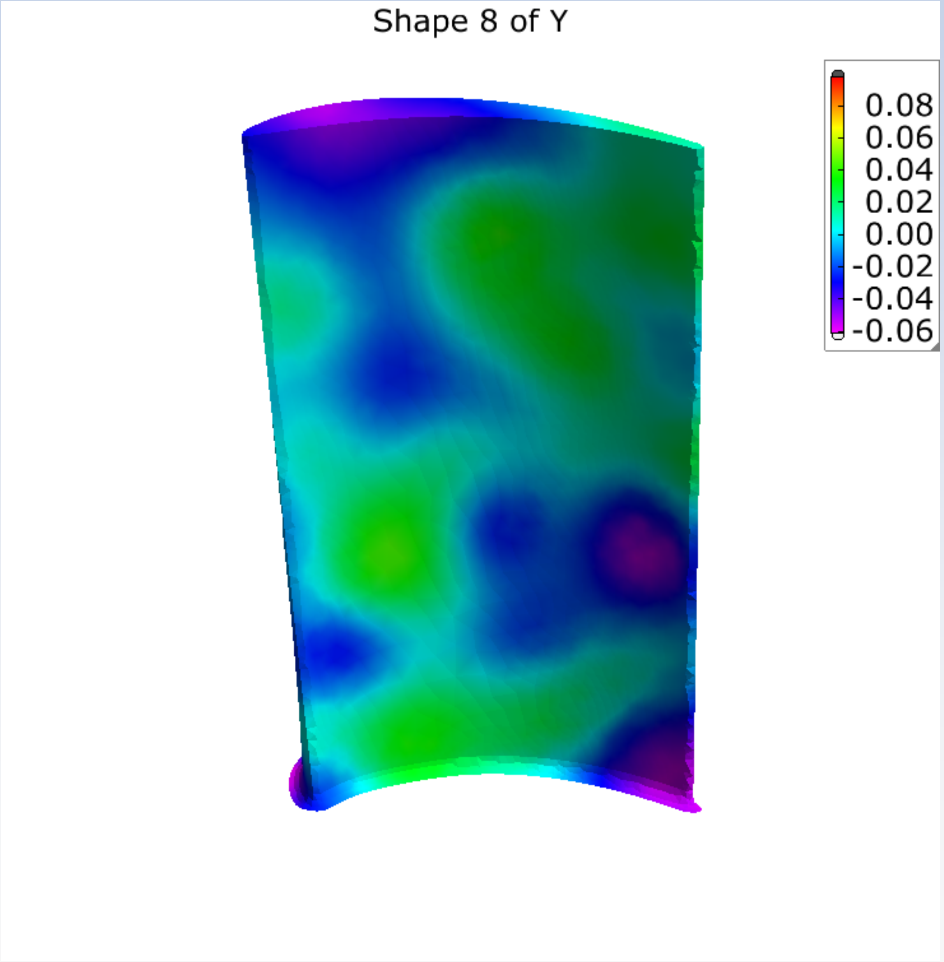


Example: Axial Turbine Blade

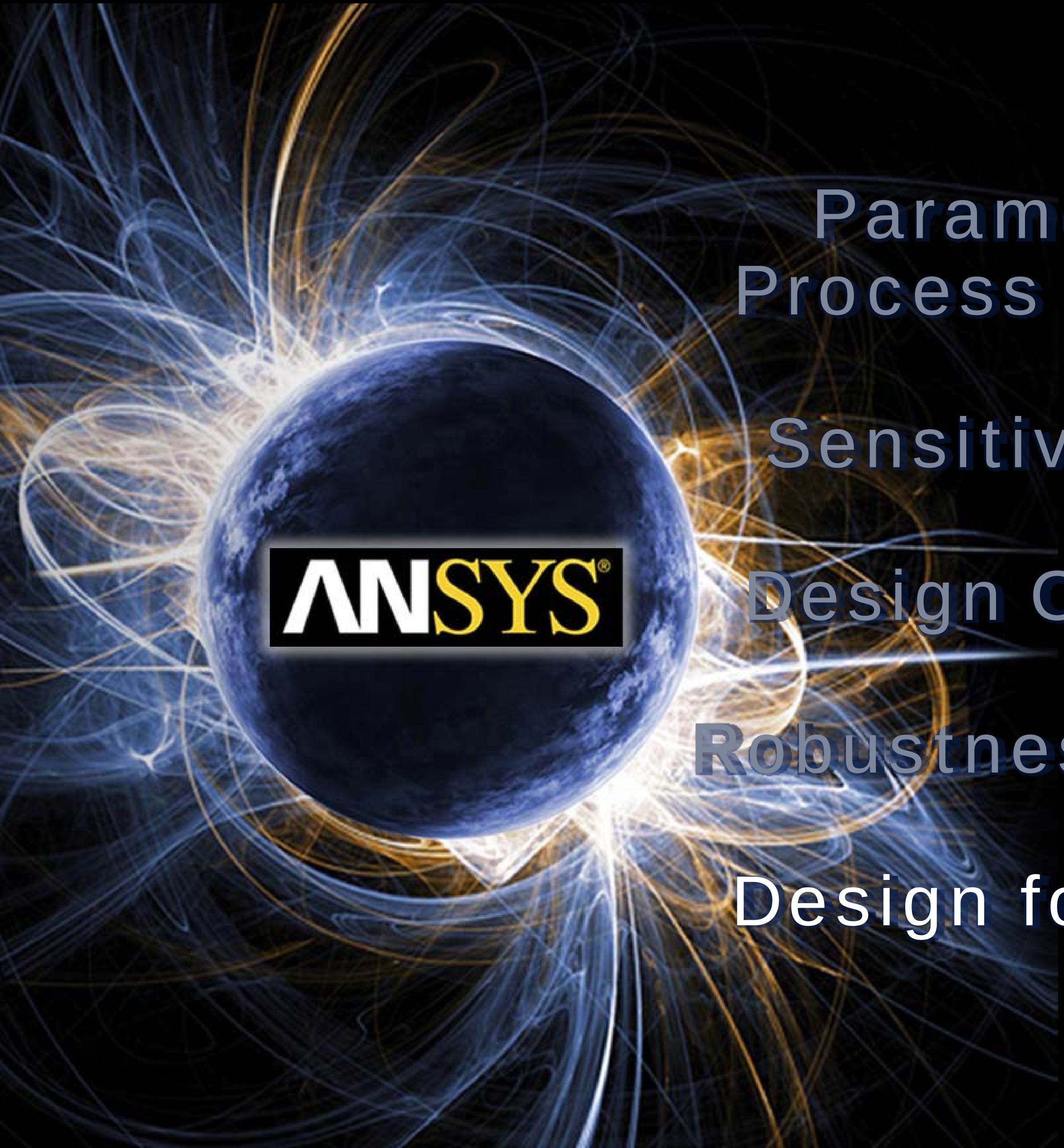
Most relevant imperfection modes :



For maximum of stresses



For efficiency



Parameterization
Process & Geometry

Sensitivity Analysis

Design Optimization

Robustness Evaluation

Design for Six Sigma

Advanced reliability analysis

Method : Adaptive Sampling on Adaptive Response Surfaces (ARSM)

Complete iterations : 3 / 3

Selected data : 2. Approximation
All samples

Number of designs : 42 (0 failed)

Number of samples :
Total : 4182 / 4182
Safe domain : 2262
Unsafe domain : 1920
Failure strings : 0

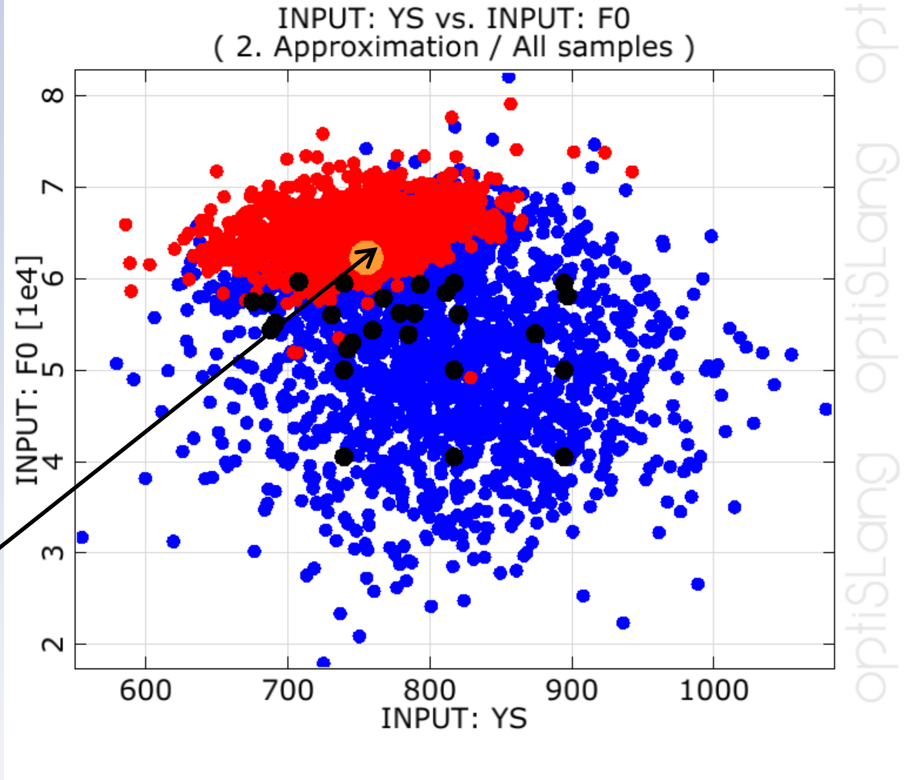
Probability of failure : 0.0002072 (0.0002072)
Standard deviation error : 6.272e-06 (6.272e-06)

Most probable failure point:

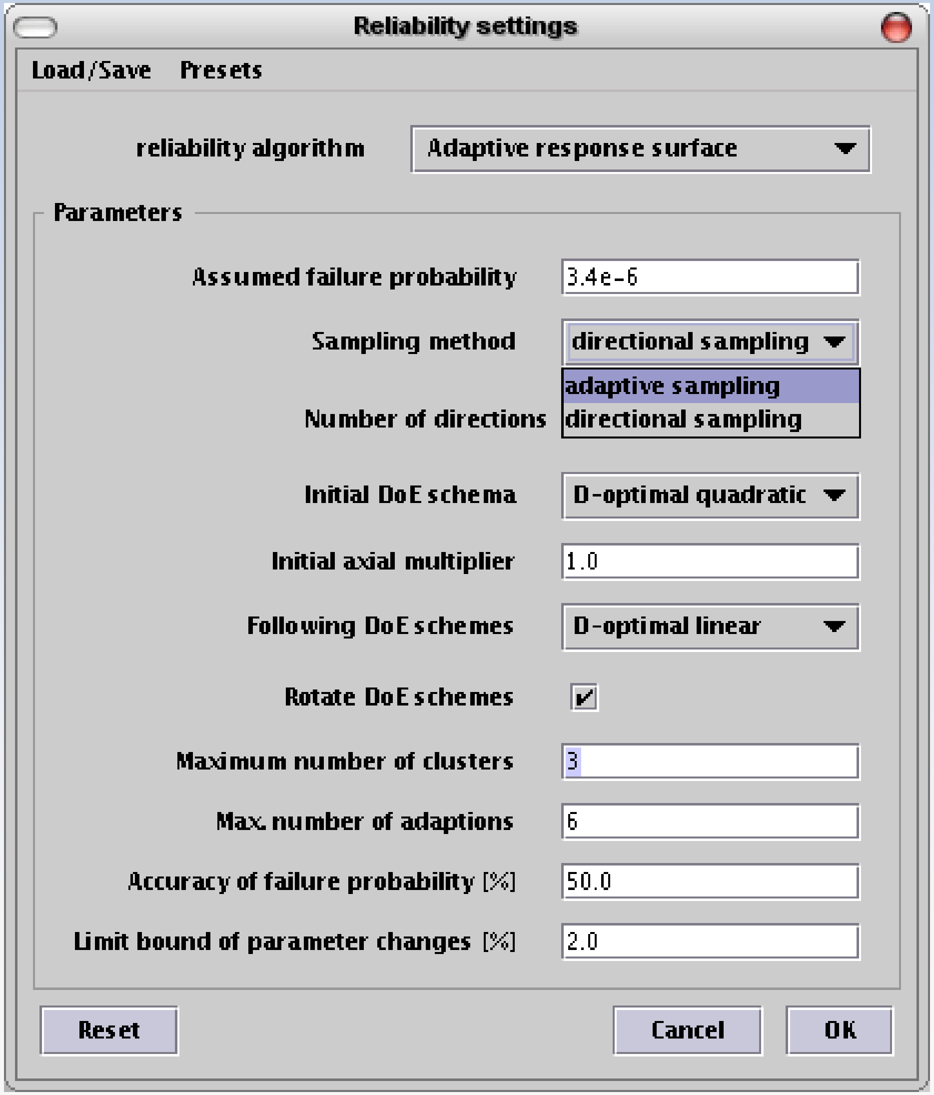
DO :68.9287850365
DA :75.5617433774
F0 :62284.2219661
YS :755.333557655

Distance median - design point (beta) : 3.349

Probability of failure (FORM): 0.0004051
Standard deviation error (FORM): 0.2986

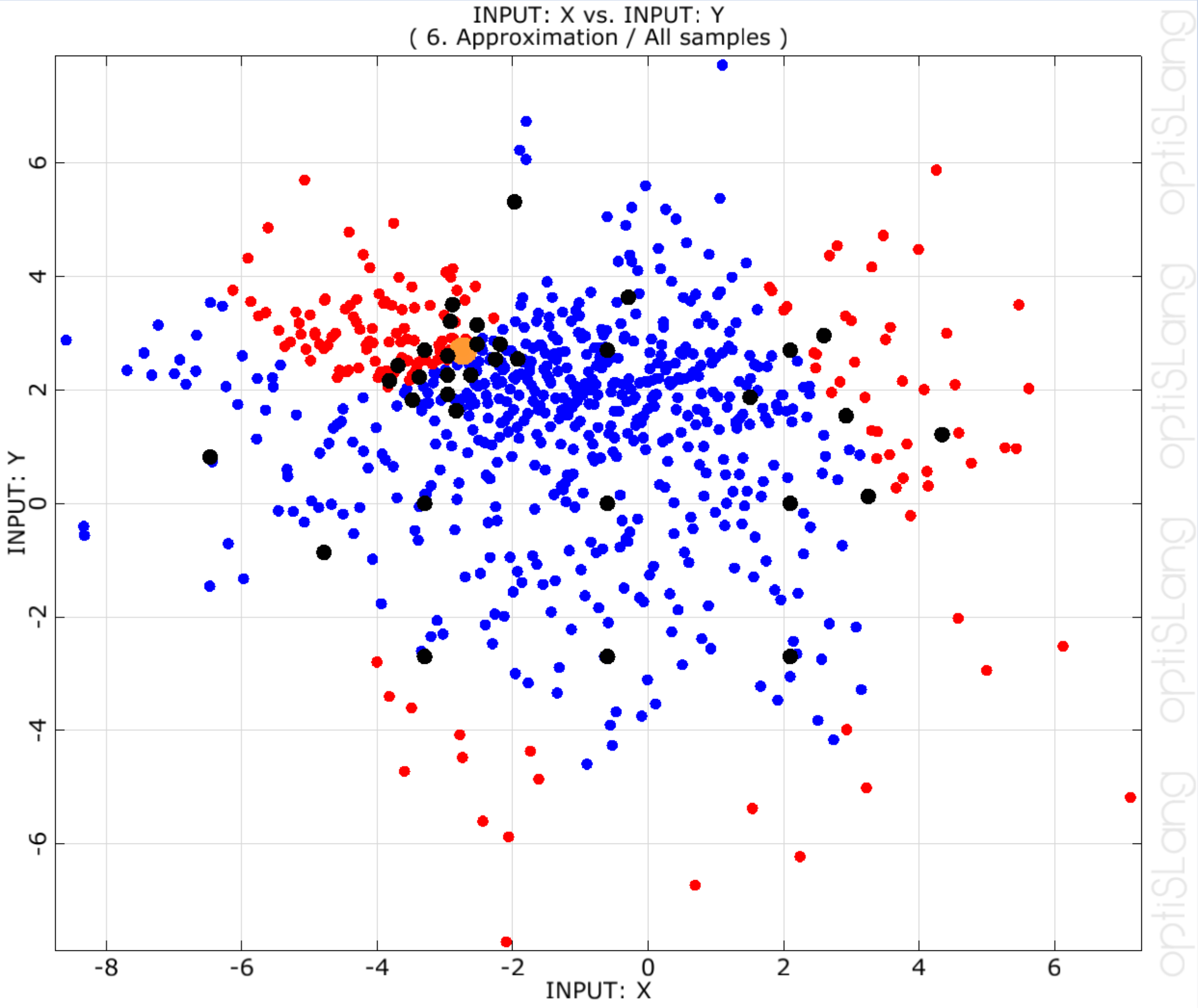


Adaptive Response Surfaces



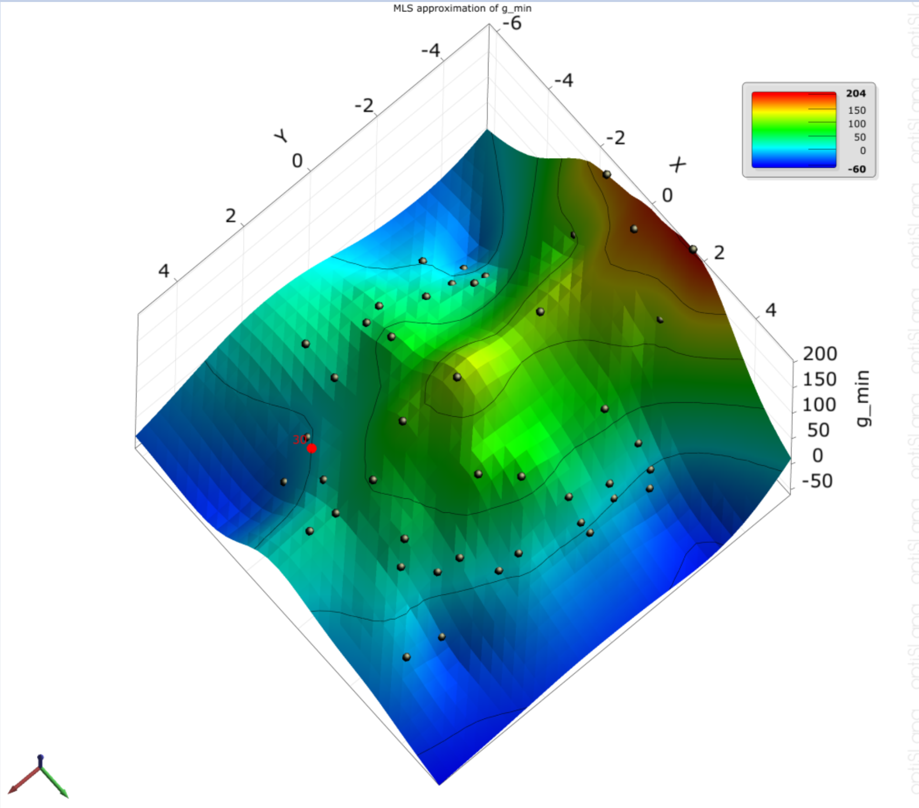
- **Sampling methods on the MLS approximation:**
  - Adaptive Sampling
  - Directional Sampling (supports more than two failure domains and sigma level independent)
- **Cluster analysis to detect number of failure domains with high failure probability**
- **Rotatable adaptive designs of experiments to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

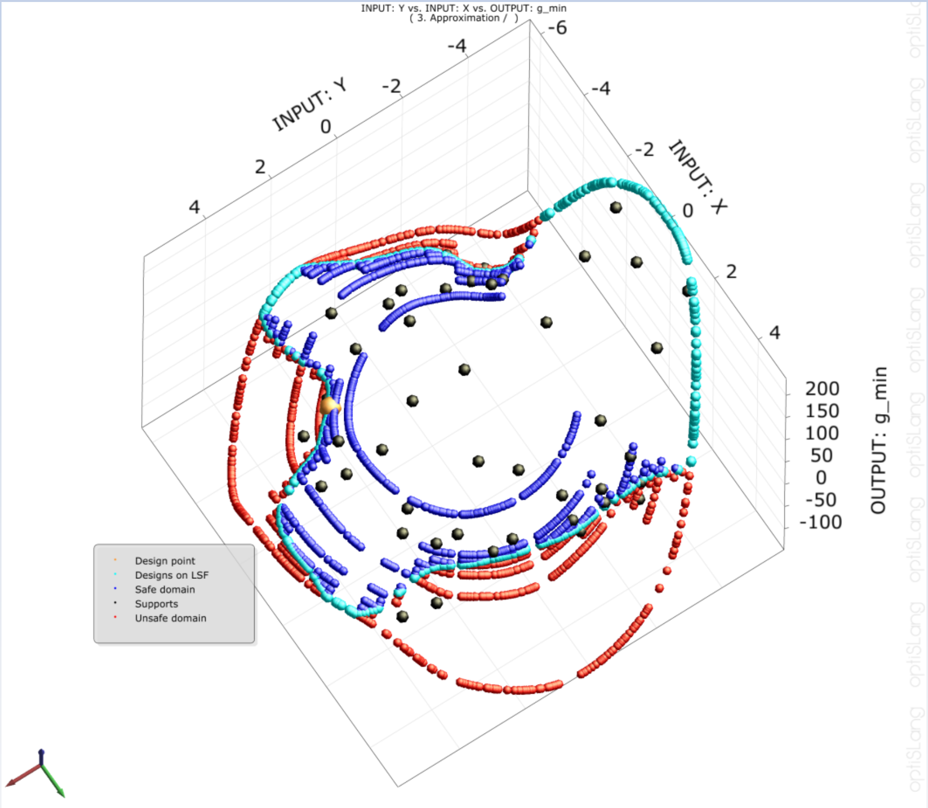
Adaptive design of experiments



- **Adaptive response surface method** with D-optimal DOE
- **Cluster analysis** to detect number of failure domains with high failure probability
- **Rotatable** adaptive designs of experiments to improve the approximation accuracy

Directional sampling on MLS





- **Sampling methods on the MLS approximation:**
  – Directional Sampling (supports more than two failure domains and sigma level independent)

Example: Axial Turbine Blade

AxialTurbine_09ROBUST.pro

Opti | Robust | Output | Limits | Strings | Constraints | Objectives

#	Name	Distribution	Mean	CoV	Stddev	Lower Cut	Upper Cut	Format	Acti...	Con...
1	myomega	Normal	-2244.215413...	-0.02	44.88430827...	-	-	%20.14f	[ ]	[x]
2	DS_hub_angle	Normal	-0.336988054...	-0.02	0.006739761...	-	-	%20.14f	[ ]	[x]
3	DS_shroud_angle	Normal	-0.178574512...	-0.02	0.003571490...	-	-	%20.14f	[ ]	[x]
4	DS_gv_angle	Normal	-9.681817021...	-0.02	0.193636340...	-	-	%20.14f	[x]	[ ]
5	Ttin	Normal	1002.859199...	0.02	20.057184	-	-	%20.14f	[x]	[ ]
6	ptin	Normal	305000.0	0.03	9150.0	-	-	%20.14f	[x]	[ ]
7	pout	Normal	87000.0	0.02	1740.0	-	-	%20.14f	[ ]	[x]
8	myAirCP	Normal	1004.4	0.03	30.13199999...	-	-	%20.14f	[ ]	[x]
9	myAirR	Normal	287.102	0.03	8.613059999...	-	-	%20.14f	[x]	[ ]
10	mySteelCP	Normal	434.0	0.05	21.70000000...	-	-	%20.14f	[ ]	[x]
11	mySteelDensity	Normal	7850.0	0.01	78.5	-	-	%20.14f	[x]	[ ]
12	mySteelLambda	Normal	60.5	0.04	2.42	-	-	%20.14f	[ ]	[x]
13	DS_FBlendRotor	Normal	0.9	0.02	0.018000000...	-	-	%20.14f	[ ]	[x]
14	Youngs_Modulus	Normal	2.0E11	0.03	6.0E9	-	-	%20.14f	[x]	[ ]
15	Poissons_Ratio	Normal	0.3	0.1	0.03	-	-	%20.14f	[x]	[ ]
16	AMP_Y_1	Normal	0.0	Infinity	0.382764141...	-	-	%20.14g	[ ]	[x]
17	AMP_Y_2	Normal	0.0	Infinity	0.007496567...	-	-	%20.14g	[ ]	[x]
18	AMP_Y_3	Normal	0.0	Infinity	0.005198775...	-	-	%20.14g	[ ]	[x]
19	AMP_Y_4	Normal	0.0	Infinity	0.003323636...	-	-	%20.14g	[x]	[ ]
20	AMP_Y_5	Normal	0.0	Infinity	0.002761396...	-	-	%20.14g	[ ]	[x]
21	AMP_Y_6	Normal	0.0	Infinity	0.001999197...	-	-	%20.14g	[ ]	[x]
22	AMP_Y_7	Normal	0.0	Infinity	0.001876365...	-	-	%20.14g	[ ]	[x]
23	AMP_Y_8	Normal	0.0	Infinity	0.001647552...	-	-	%20.14g	[x]	[ ]
24	AMP_Y_9	Normal	0.0	Infinity	0.001336831...	-	-	%20.14g	[ ]	[x]
25	AMP_Z_1	Normal	0.0	Infinity	0.287083430...	-	-	%20.14g	[ ]	[x]
26	AMP_Z_2	Normal	0.0	Infinity	0.005418631...	-	-	%20.14g	[ ]	[x]
27	AMP_Z_3	Normal	0.0	Infinity	0.003693600...	-	-	%20.14g	[ ]	[x]
28	AMP_Z_4	Normal	0.0	Infinity	0.002228785...	-	-	%20.14g	[ ]	[x]
29	AMP_Z_5	Normal	0.0	Infinity	0.001987426...	-	-	%20.14g	[ ]	[x]
30	AMP_Z_6	Normal	0.0	Infinity	0.001529446...	-	-	%20.14g	[ ]	[x]
31	AMP_Z_7	Normal	0.0	Infinity	0.001421394...	-	-	%20.14g	[ ]	[x]
32	AMP_Z_8	Normal	0.0	Infinity	0.001041140...	-	-	%20.14g	[ ]	[x]
33	AMP_Z_9	Normal	0.0	Infinity	9.208922689...	-	-	%20.14g	[ ]	[x]

Cancel | OK

Reliability settings

Load/Save | Presets

reliability algorithm: Adaptive response surface

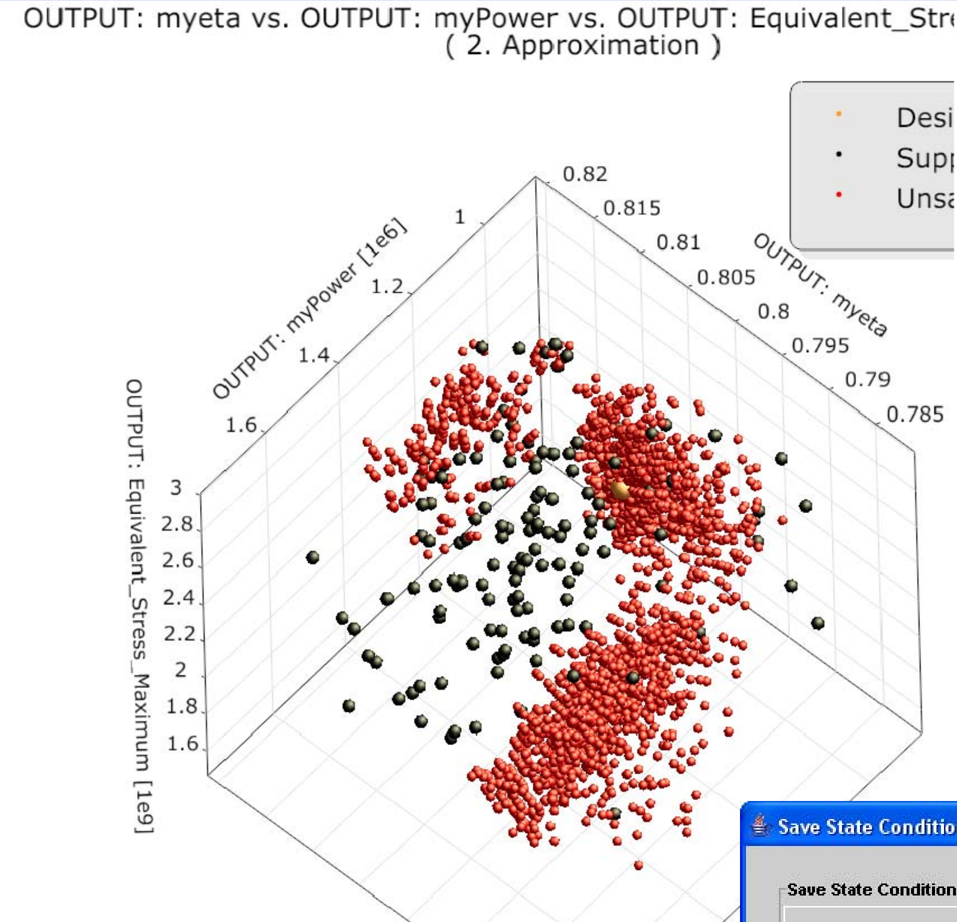
Parameters

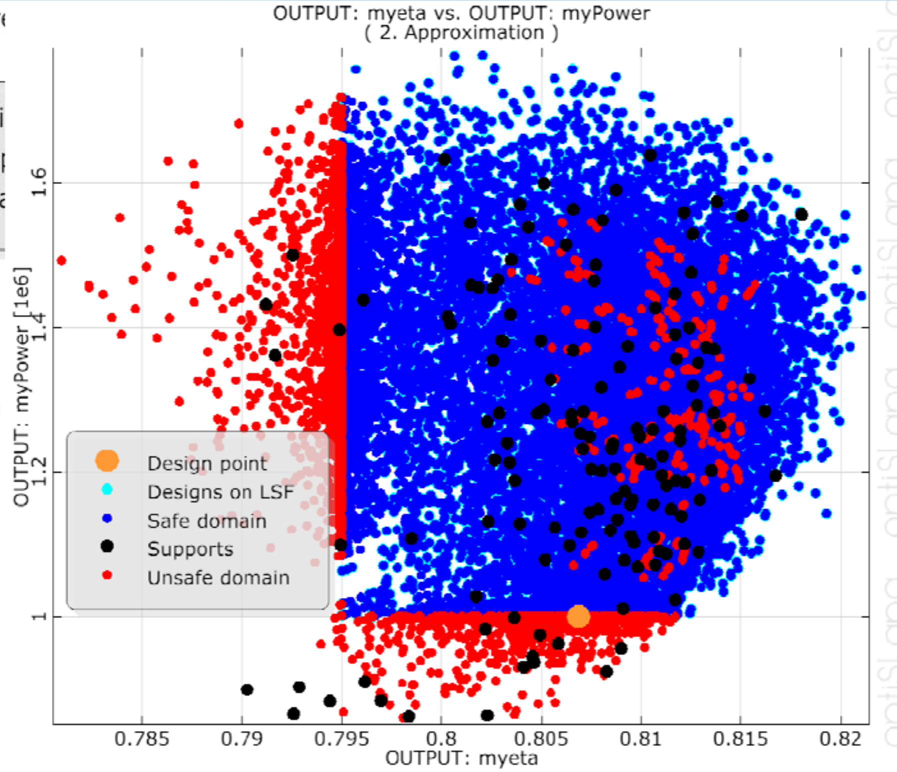
- Assumed failure probability: 3.4e-6
- Sampling method: directional sampling
- Number of directions: 10000
- Initial DoE schema: D-optimal quadratic
- Initial axial multiplier: 1.0
- Following DoE schemes: D-optimal linear
- Rotate DoE schemes: [ ]
- Maximum number of clusters: 6
- Max. number of adaptions: 6
- Accuracy of failure probability [%]: 10
- Limit bound of parameter changes [%]: 2.0

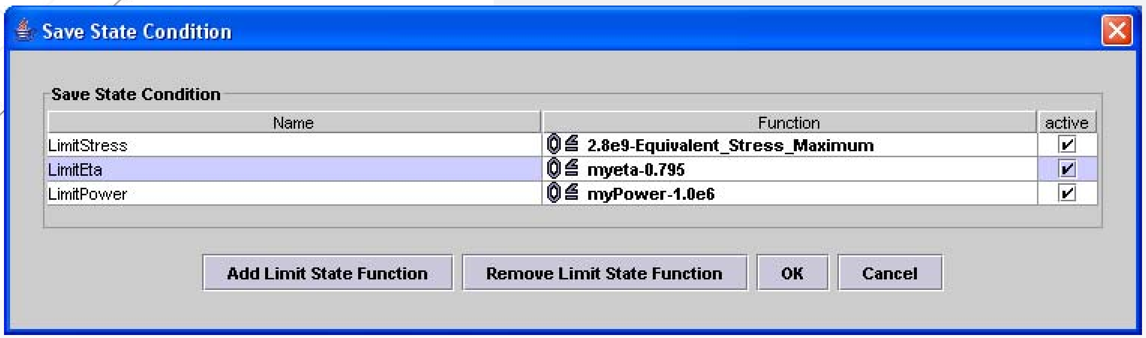
Reset | Cancel | OK

- **n = 9 relevant random parameters**

Example: Axial Turbine Blade






Save State Condition

Save State Condition

Name	Function	active
LimitStress	2.8e9-Equivalent_Stress_Maximum	✓
LimitEta	myeta-0.795	✓
LimitPower	myPower-1.0e6	✓

Add Limit State Function | Remove Limit State Function | OK | Cancel

- **3 clustered areas with high failure probability**

Reliability Analysis

- **n = 9 random parameters**
- **N = 141 design evaluations**
- **Pf = 2.4e-7 < 3.4e-6 (4.5 sigma)**
- **Six Sigma Design**

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

Selected data : 2. Approximation

Number of designs : 141 (7 failed)

Complete directions : 10000 / 10000

Number of samples :
Total : 19590
Safe domain : 15143
Unsafe domain : 4447
Failure strings : 0
Unsuccessful : 0

Probability of failure : 2.45e-07 (2.45e-07)
Standard deviation error : 4.771e-08 (4.771e-08)

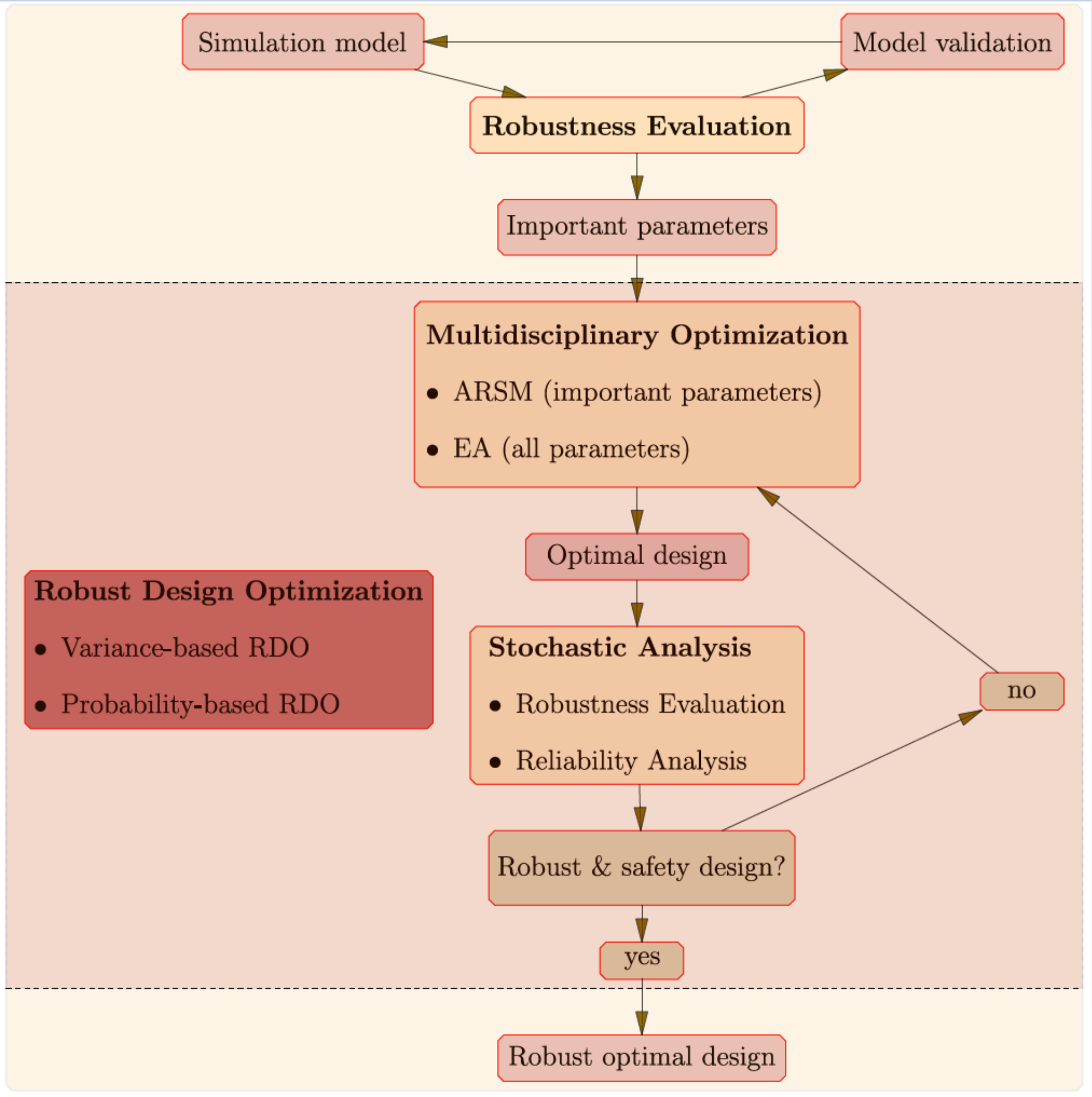
Most probable failure point:

myomega :-2217.04008841
DS_gv_angle :-9.99561718295
Ttin :960.730885684
ptin :266629.901461
pout :90929.4317189
myAirCP :1023.31803947
myAirR :279.505216069
Youngs_Modulus :202109405683
Poissons_Ratio :0.285449914136

Distance median - design point (beta) : 5.623

Probability of failure (FORM): 9.372e-09

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

Summary

- **Workbench supports full Workflow**
  - Geometry, Meshing, Simulation, Post-Processing
- **Multi Physics support**
- **Parametric Workflow management**
- **Automatic and embedded solution procedure**
- **Parallel and distributed solver runs**
- **Process integration within optiSLang**
- **Robust Design Optimization with respect to 7 design parameters and 15 random geometry parameters, including the manufactoring tolerances based on measurements**
- **Optimized robust design**
- **Optimized Six Sigma design**
- **N = 36 + 257 + 84 + 47 + 141 = 565 design evaluations**
  (SA)(EA)(ARSM)(RE)(RA)
- **Calculation time: 48 hours (8 CPUs)**