Optimization and Robustness Evaluation of an Axial Turbine using Fluid-Structure Interaction

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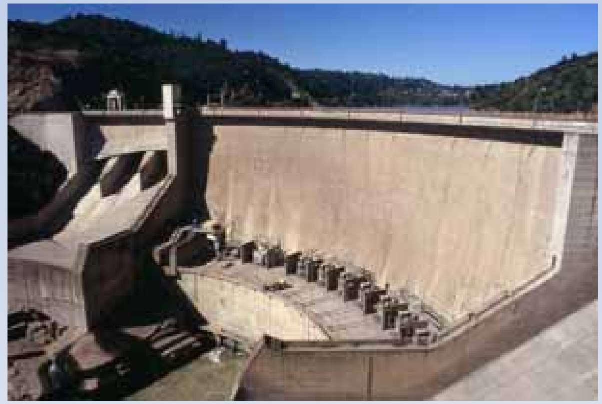
Outline

- **Parametric Process Integration**
- **Sensitivity Analysis**
- **Design Optimization**
  - Evolutionary Algorithm
  - Adaptive Response Surface Method
- **Robustness Evaluation**
- **Outlook**
  - Random Fields
  - Design for Six Sigma (Reliability Analysis)

Motivation



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

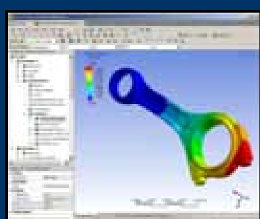
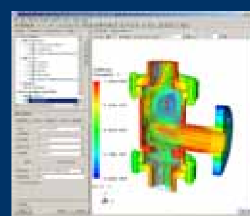
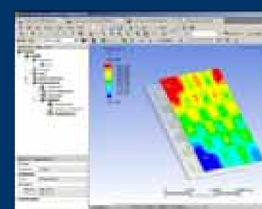
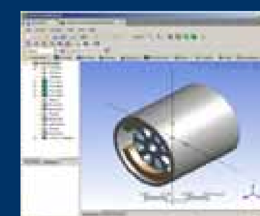
Workbench Platform & optiSLang

ANSYS

CATIA SolidWorks UGS **CAD / PDM** PTC autodesk

ANSYS Workbench

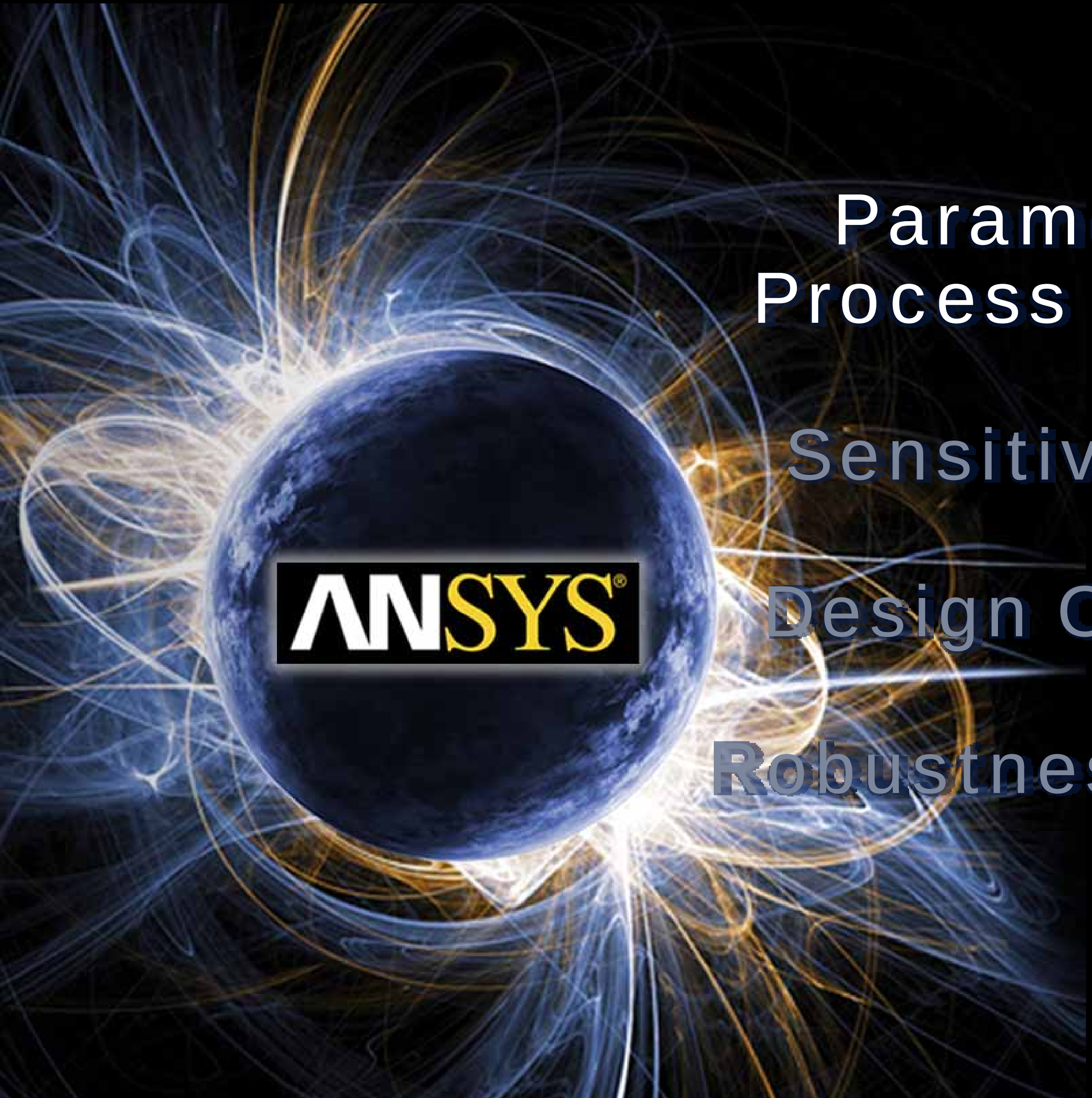
Structural Mechanics - Fluid Dynamics - Heat Transfer - Electromagnetic

A Multi-Physics Design and Analysis System

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

optiSLang



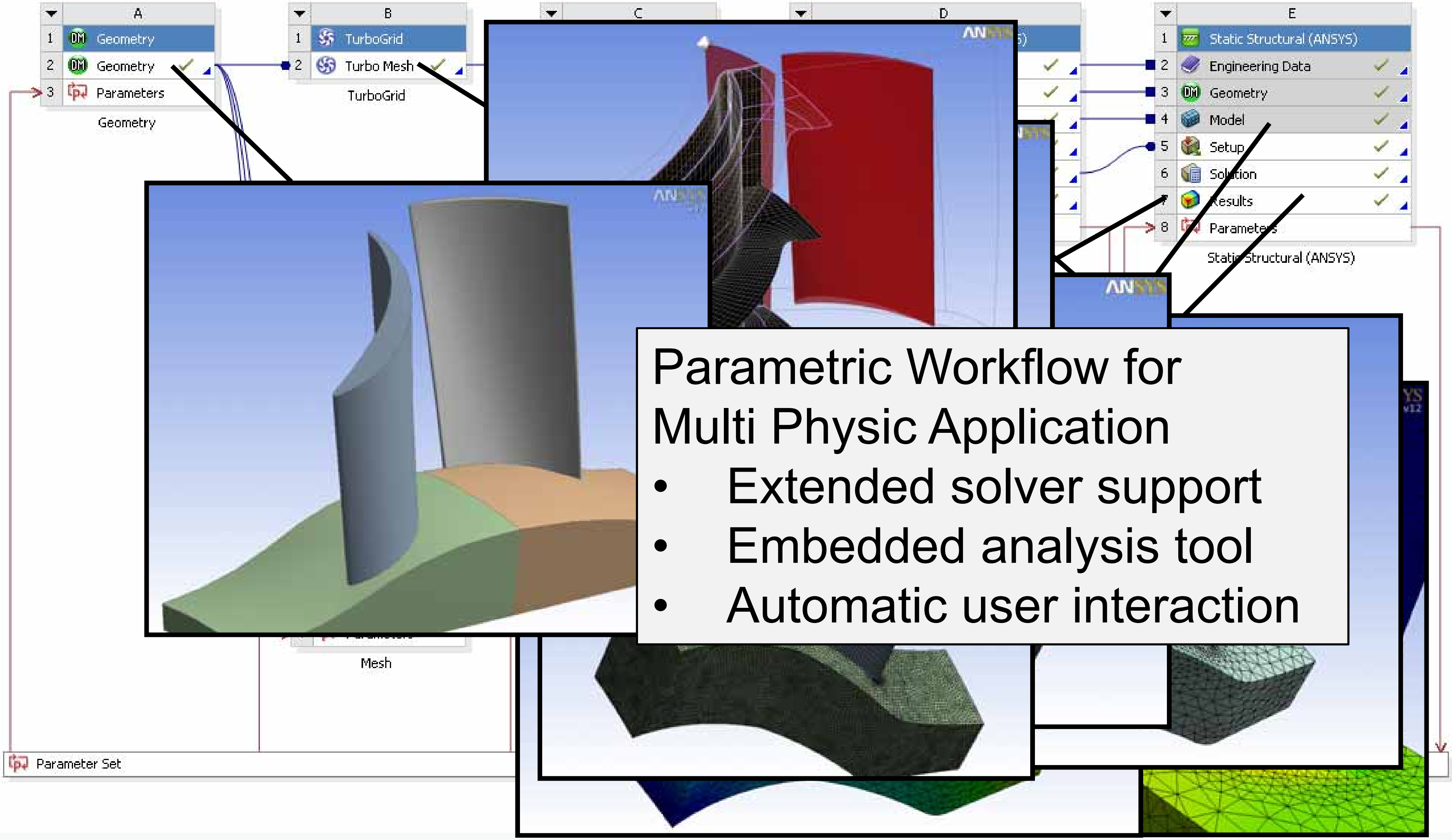
Parameterization Process & Geometry

Sensitivity Analysis

Design Optimization

Robustness Evaluation

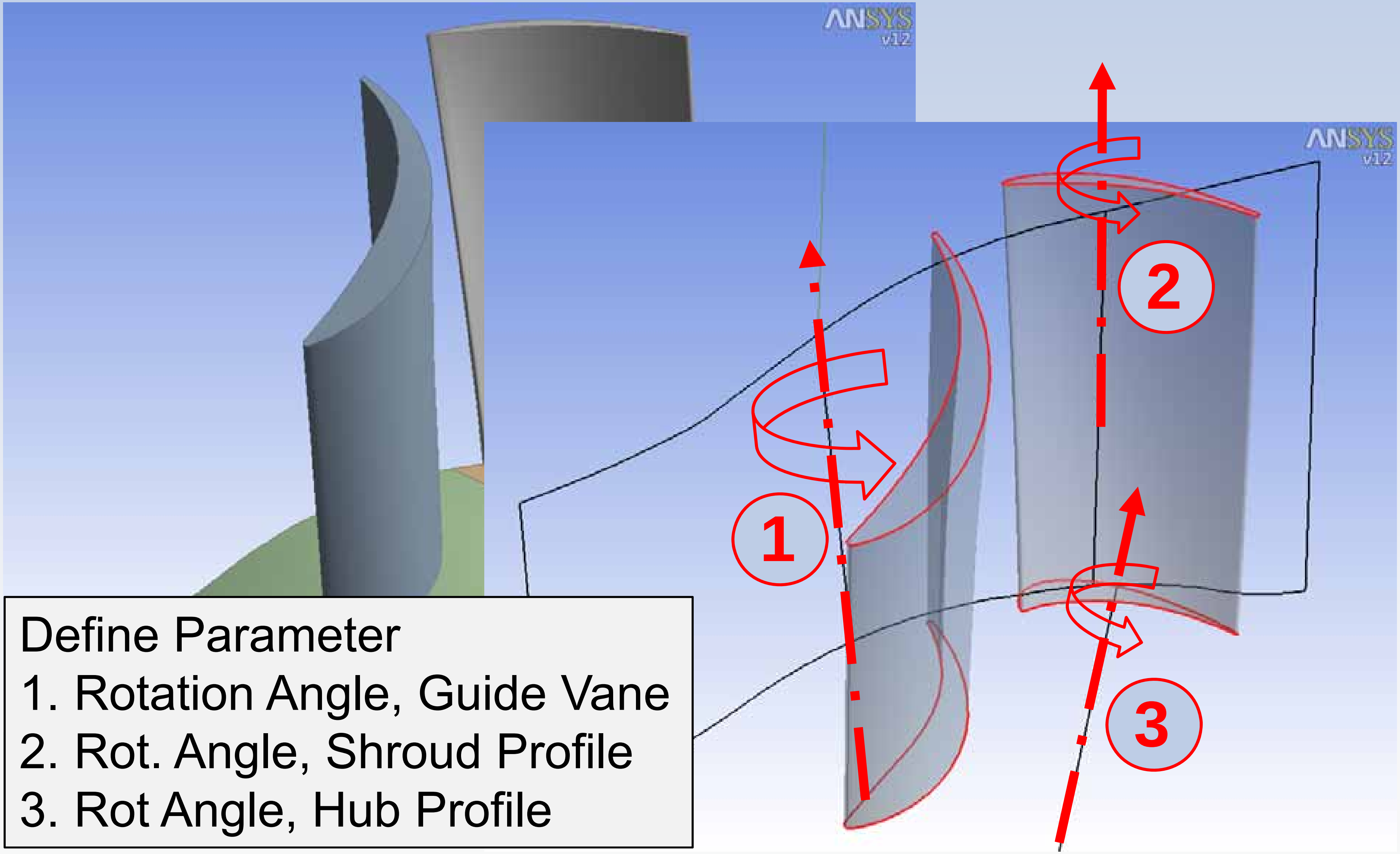
Parameterization of the Workflow



Parametric Workflow for
Multi Physic Application

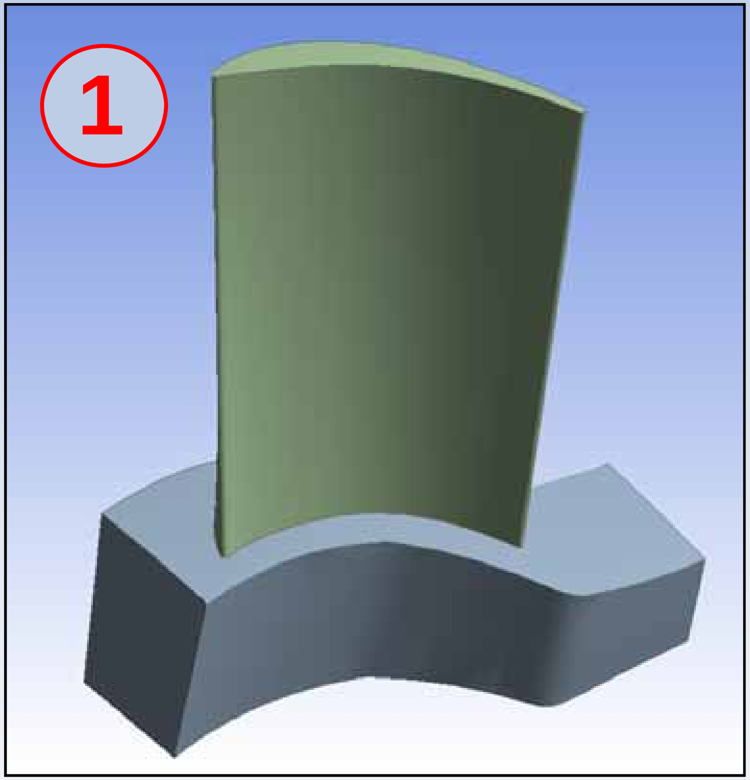
- Extended solver support
- Embedded analysis tool
- Automatic user interaction

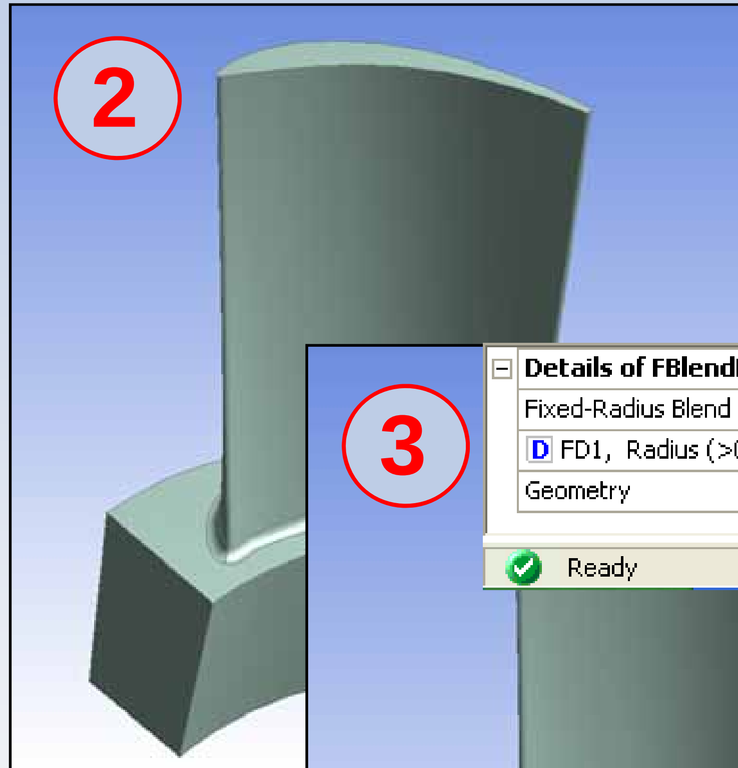
Parameterization of the Geometry

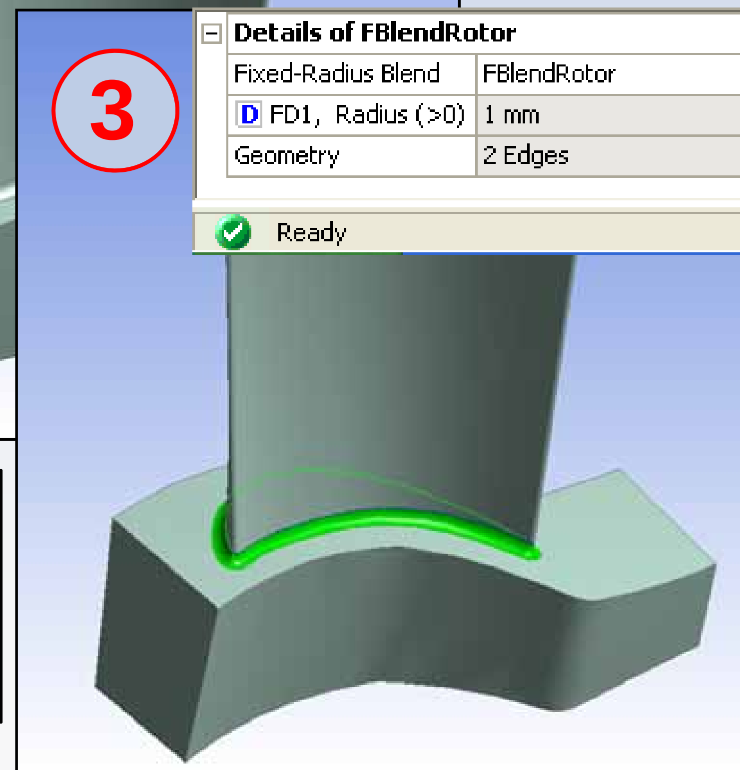


Define Parameter
1. Rotation Angle, Guide Vane
2. Rot. Angle, Shroud Profile
3. Rot Angle, Hub Profile

Parameterization of the Geometry

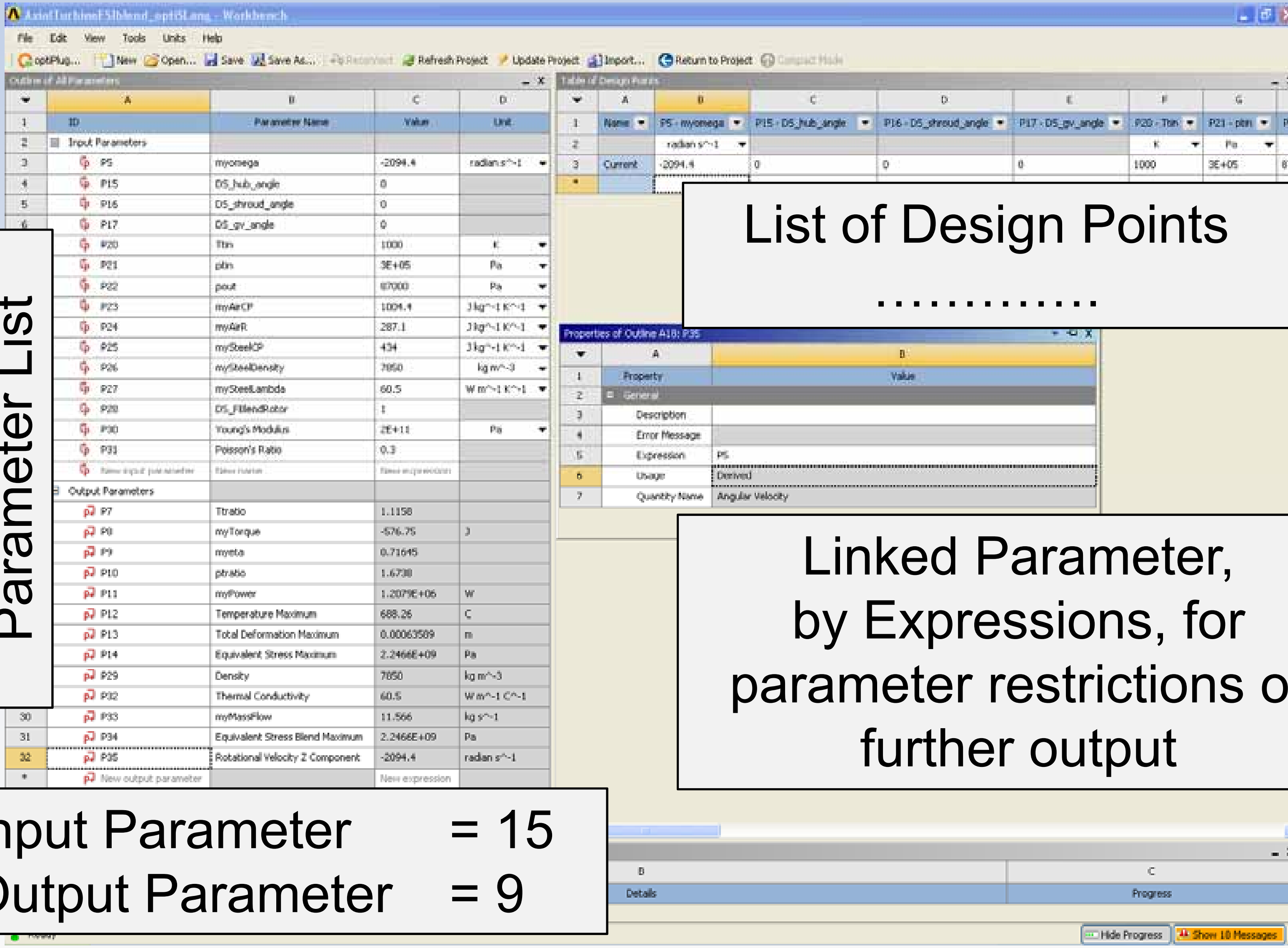






1. CHT Model: Multi Body Part
2. CSD Model: Single Part
3. Add Blend for CSD, as Parameter

Parameter Manager



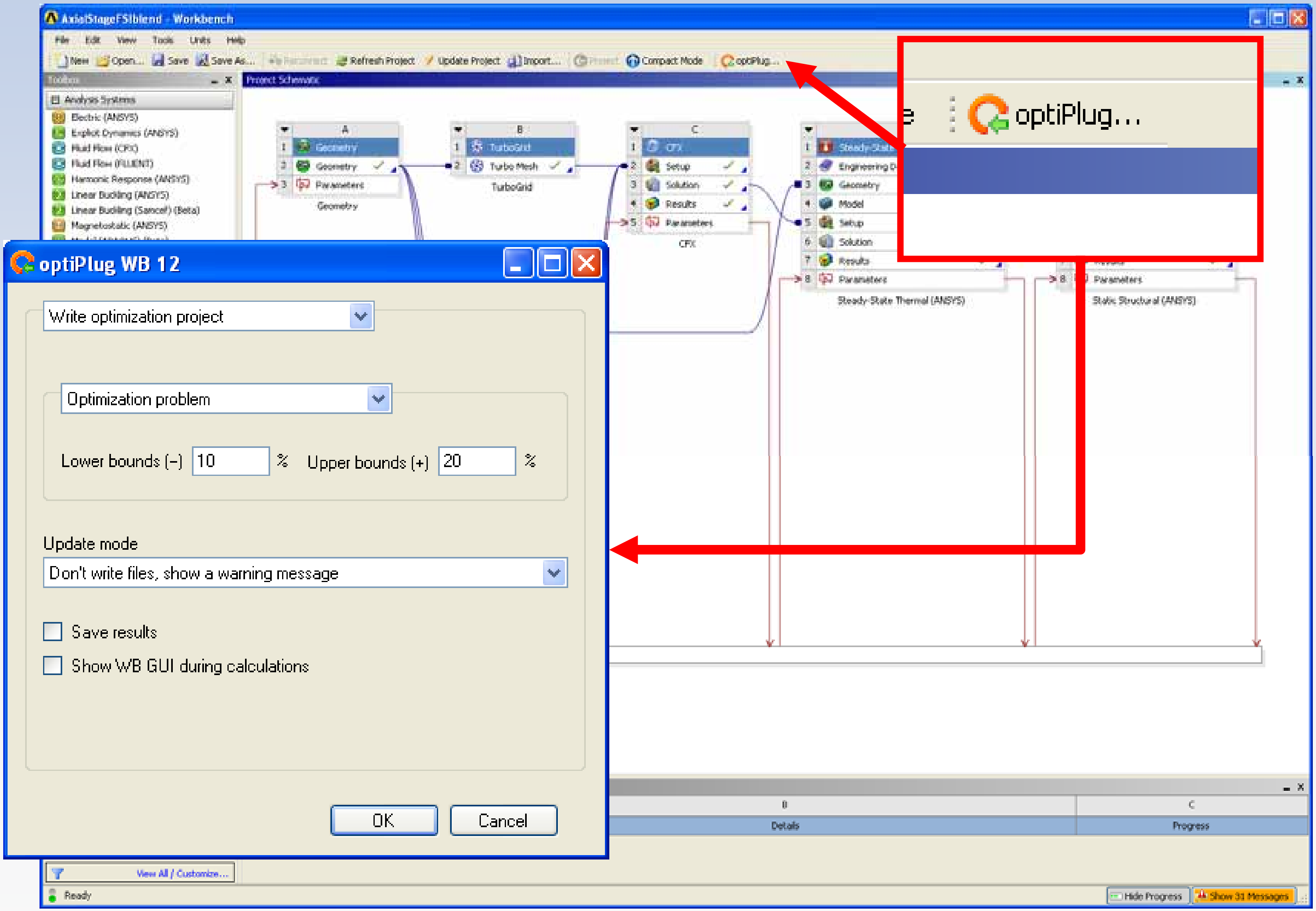
Parameter List

List of Design Points
....

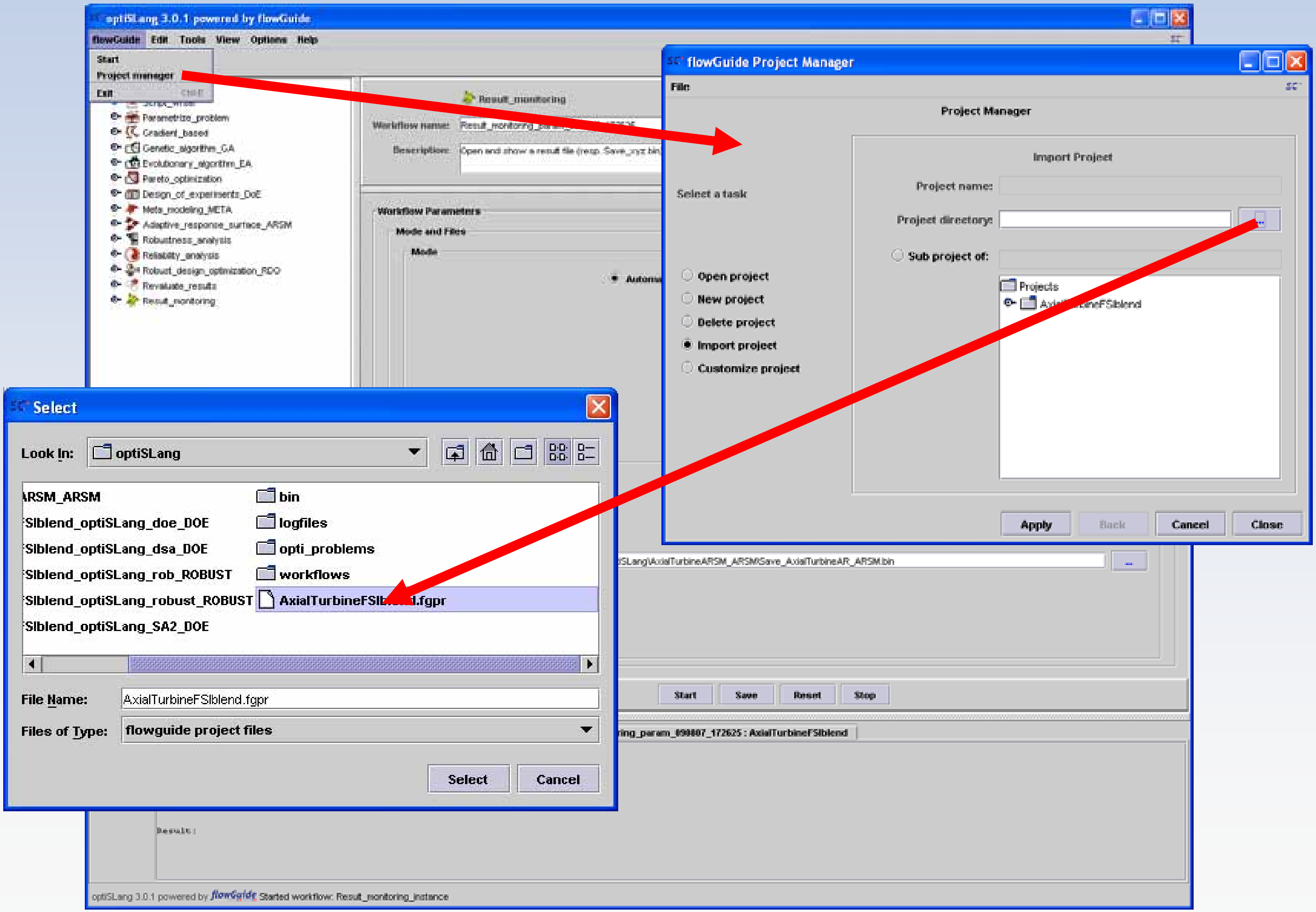
Linked Parameter,
by Expressions, for
parameter restrictions or
further output

Input Parameter = 15
Output Parameter = 9

Workbench Interface to optiSLang



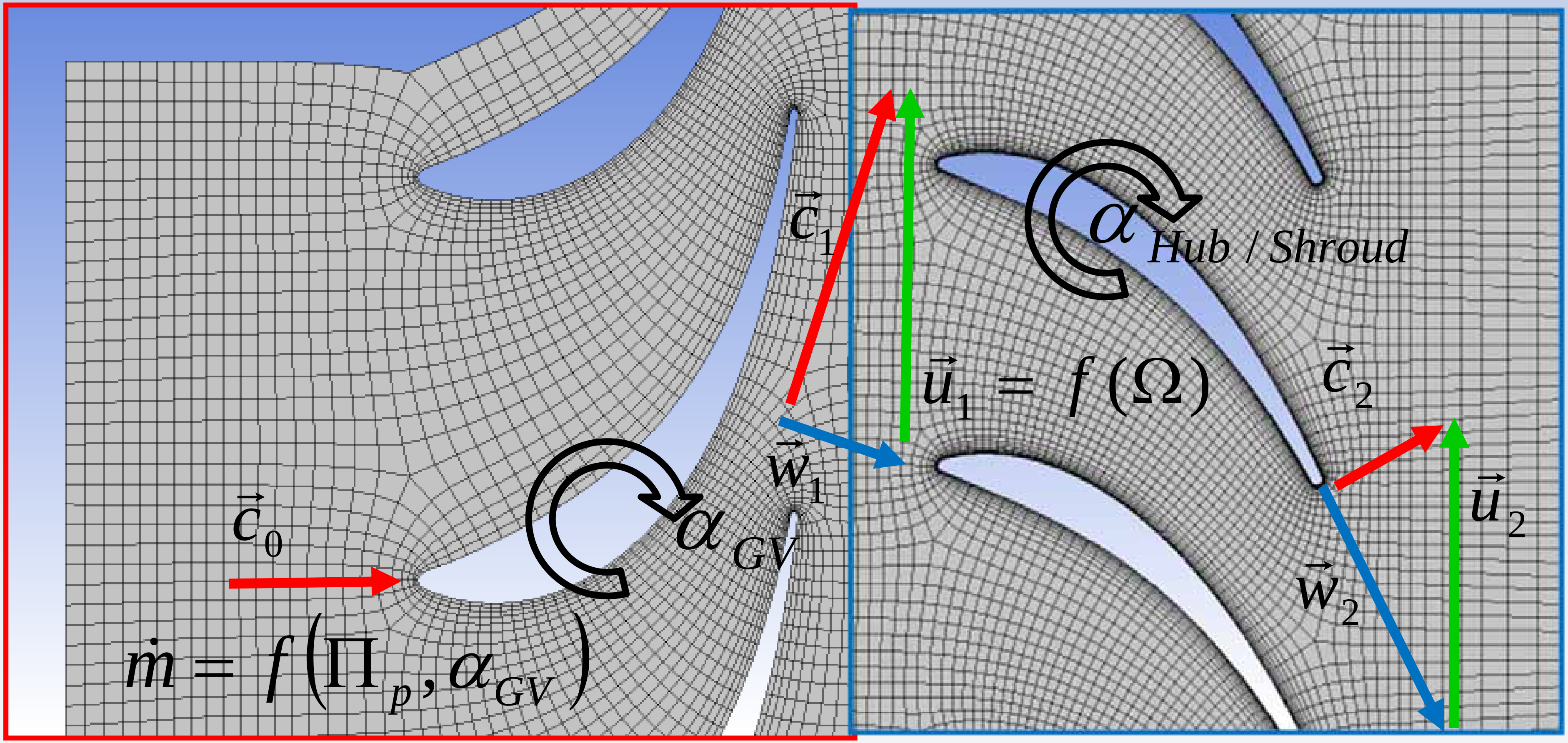
Workbench Interface to optiSLang



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

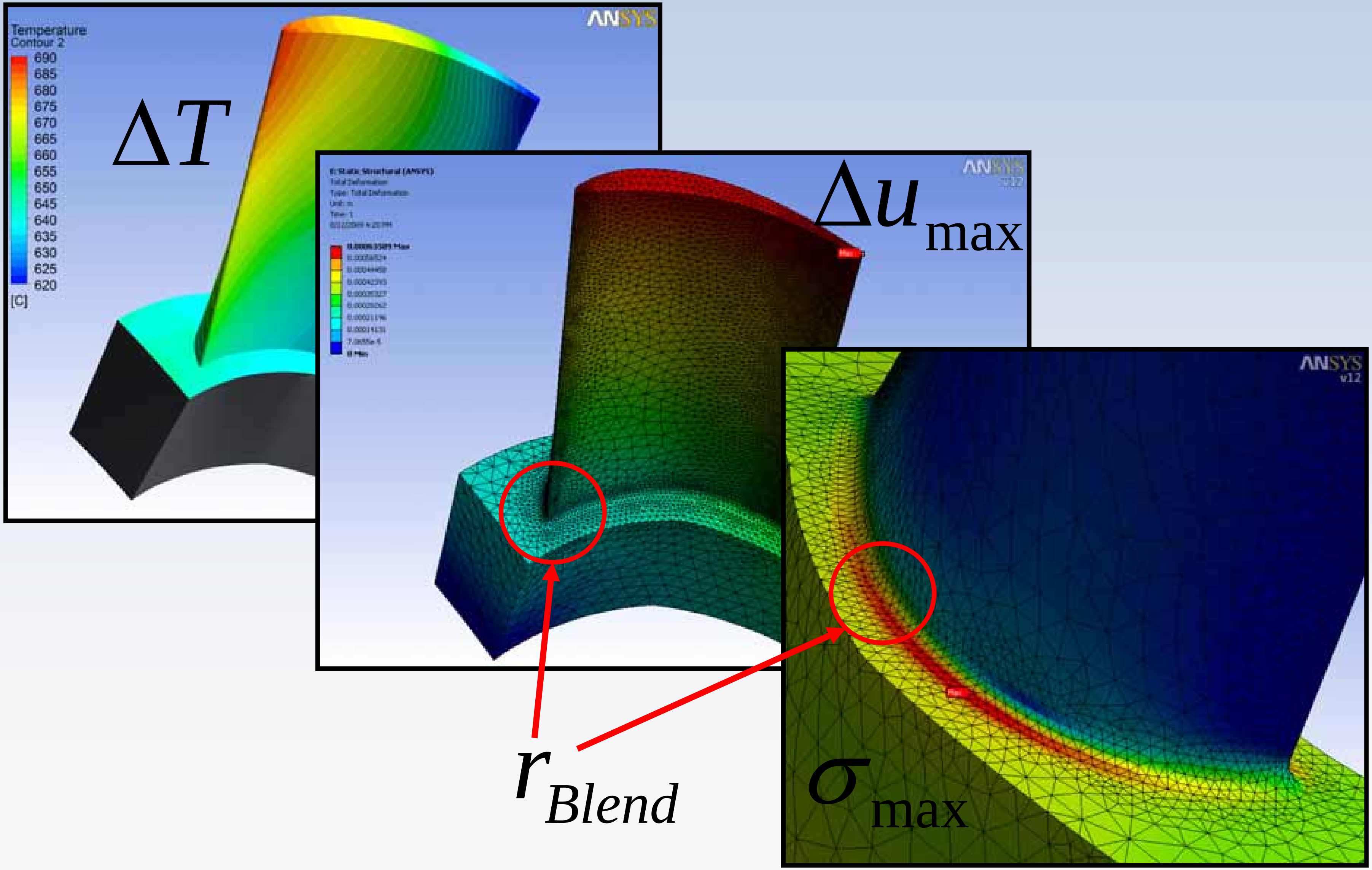
Parameter Physics, Fluid Flow

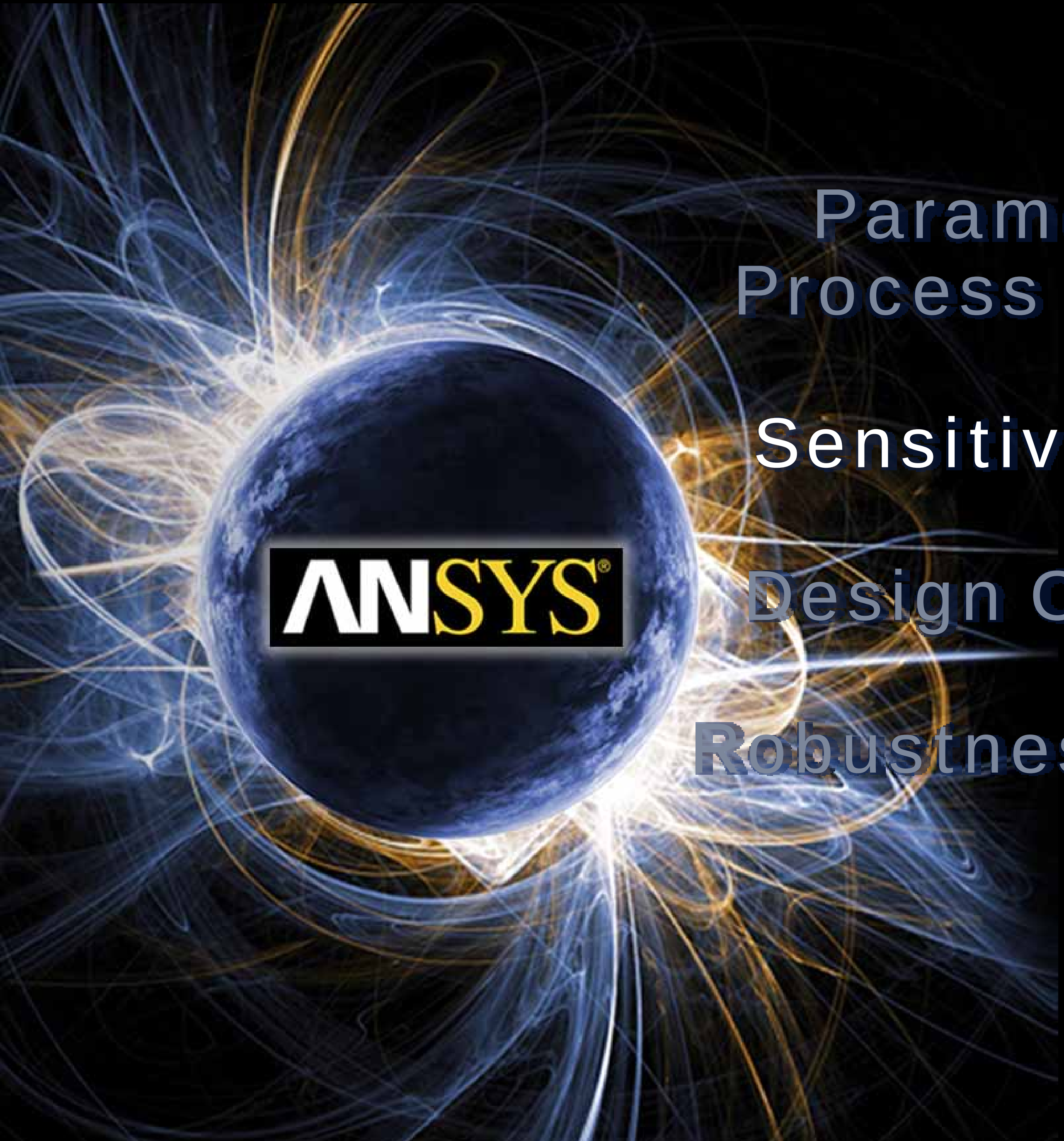


$$\boxed{\eta = f\left(\Theta_T, \Pi_p\right)}$$

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

Parameter Physics, Mechanic





Parameterization
Process & Geometry

Sensitivity Analysis

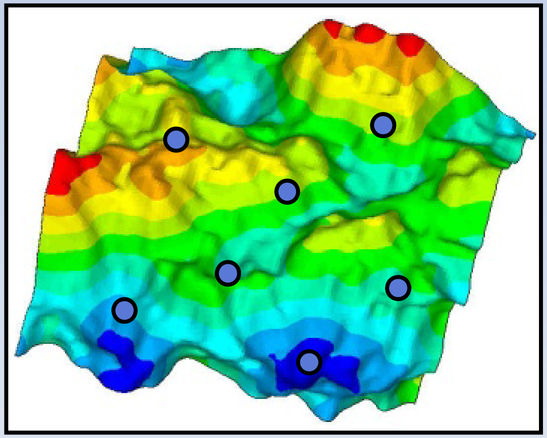
Design Optimization

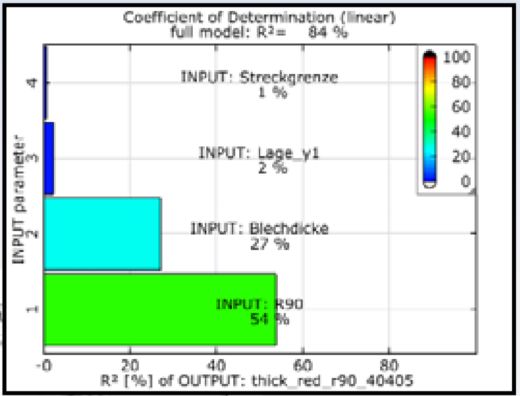
Robustness Evaluation

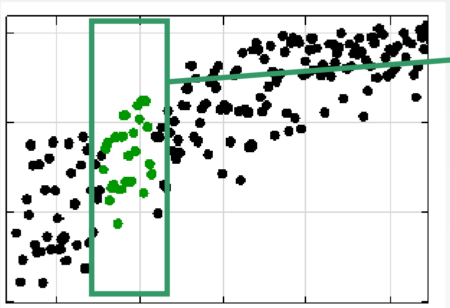
Sensitivity Analysis

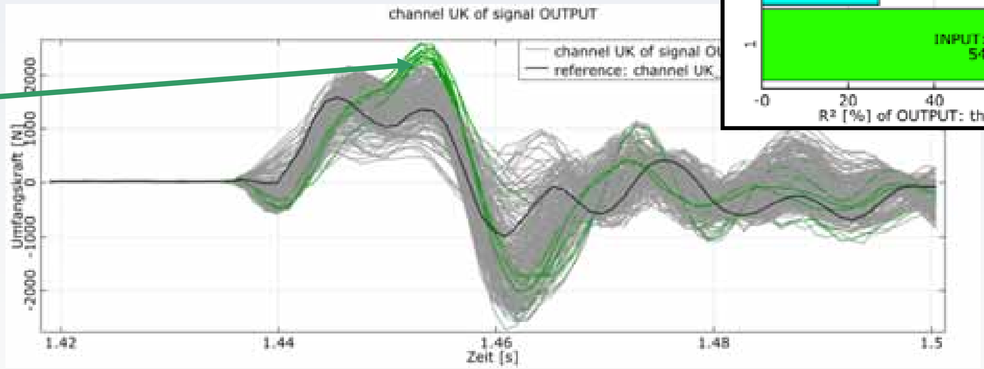
1. Scanning the Design Space with optimized LHS, variation and correlation are investigated

2. Identification of important variables
    - Check Variation of Design Space
    - Check Coefficient of Importance

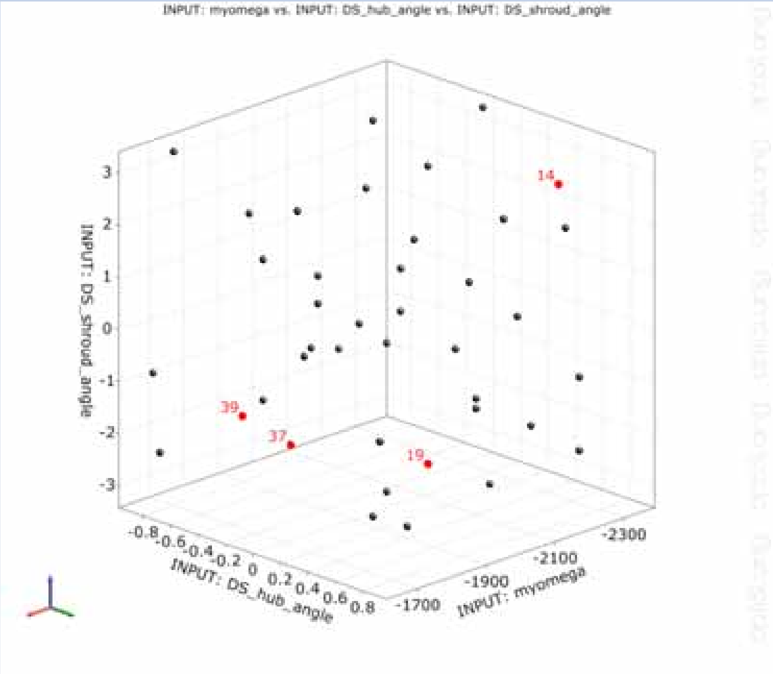


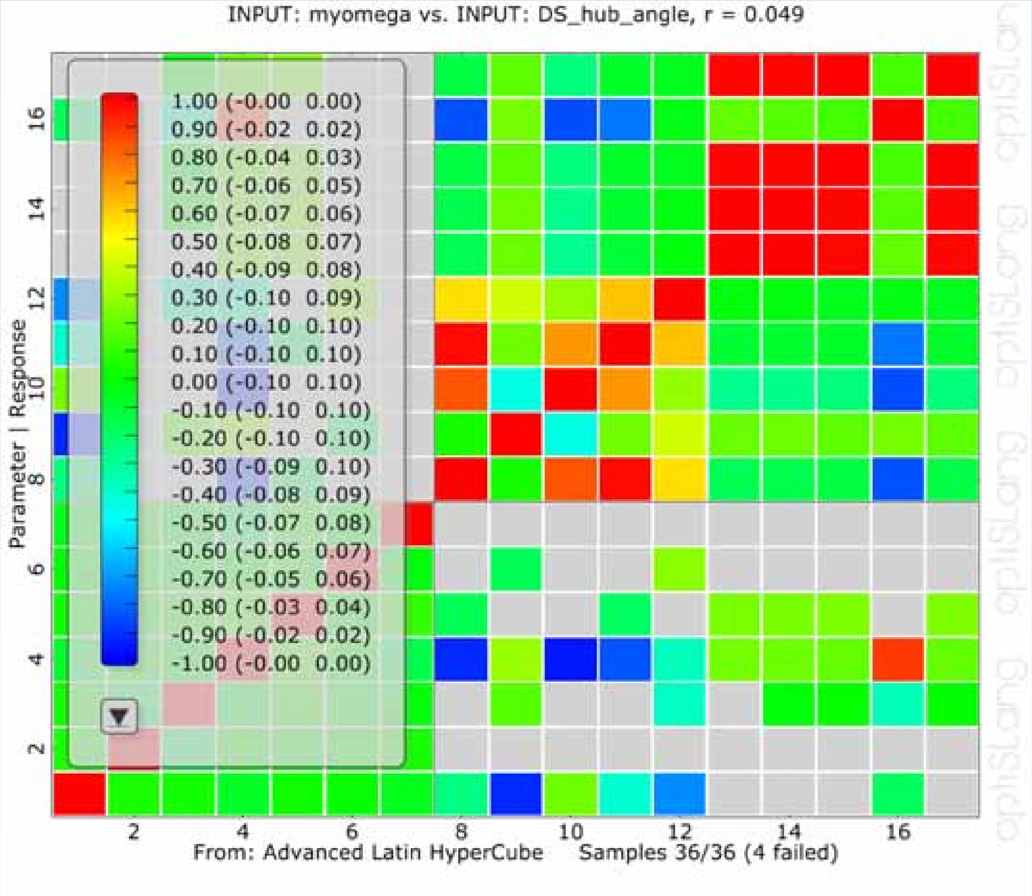






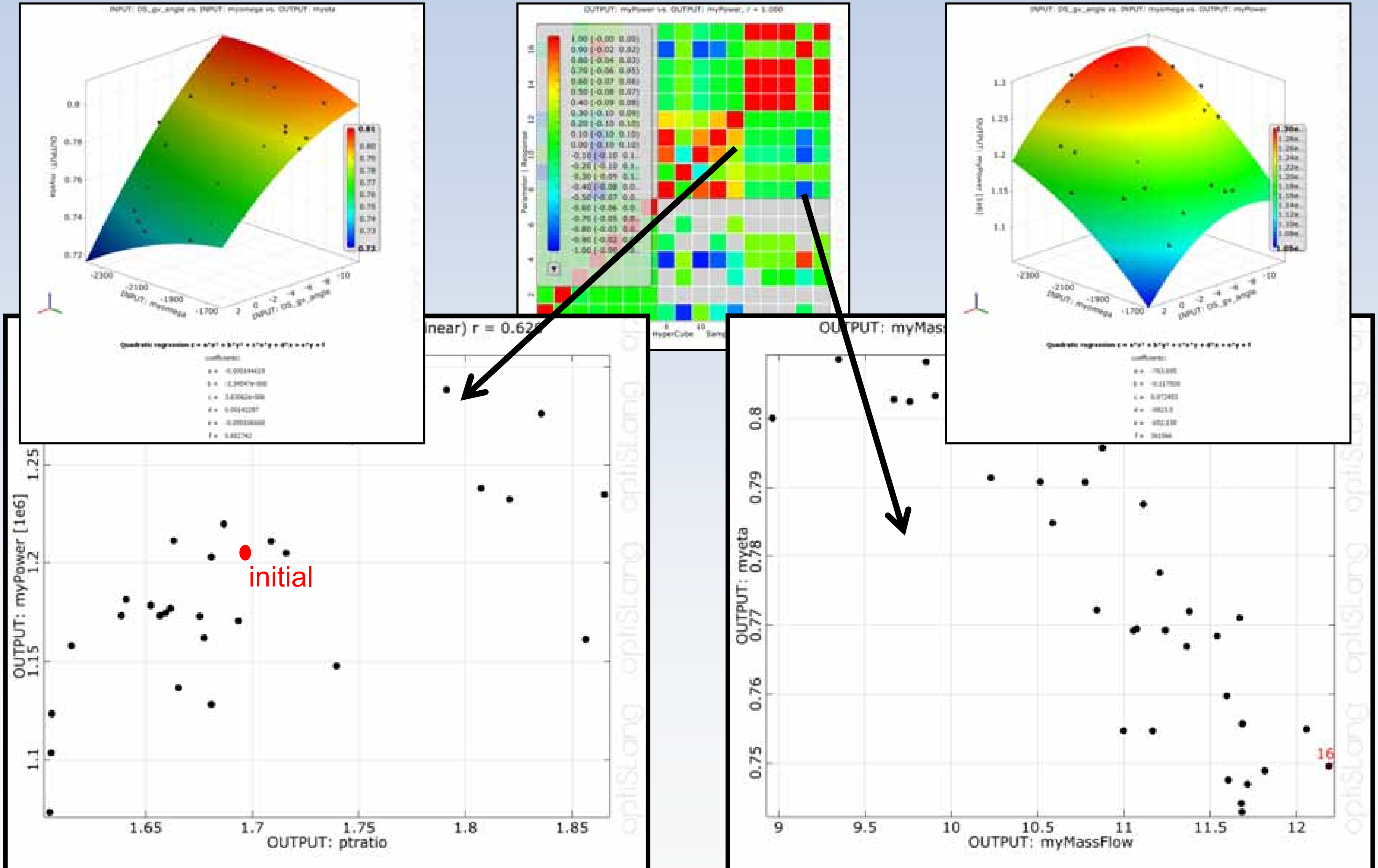
Latin Hypercube and Confidences





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

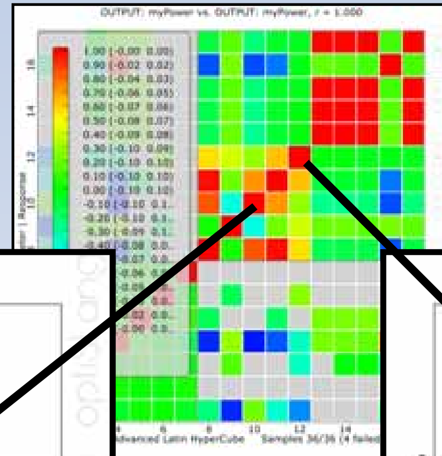
Variation of Design Space

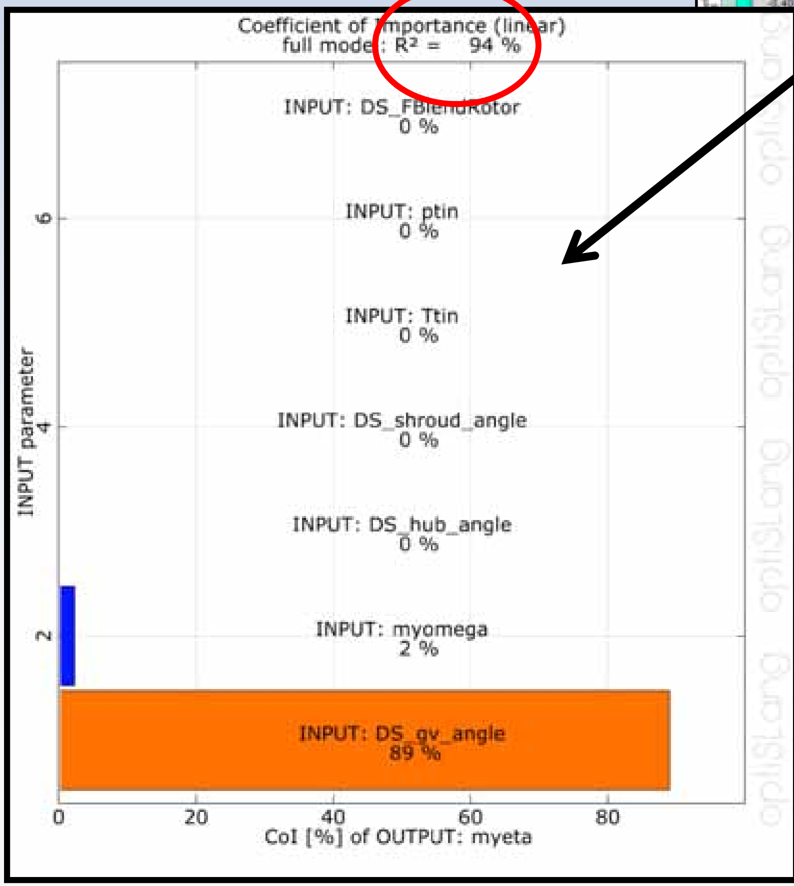


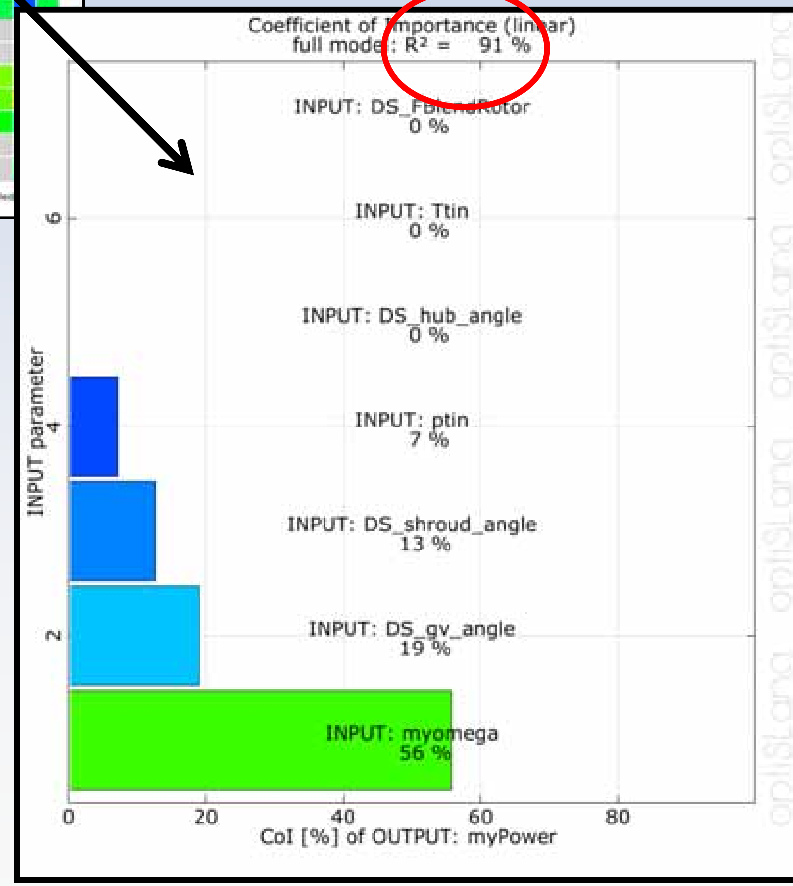
Coefficient of Importance, CoI

CoI=94%>80%

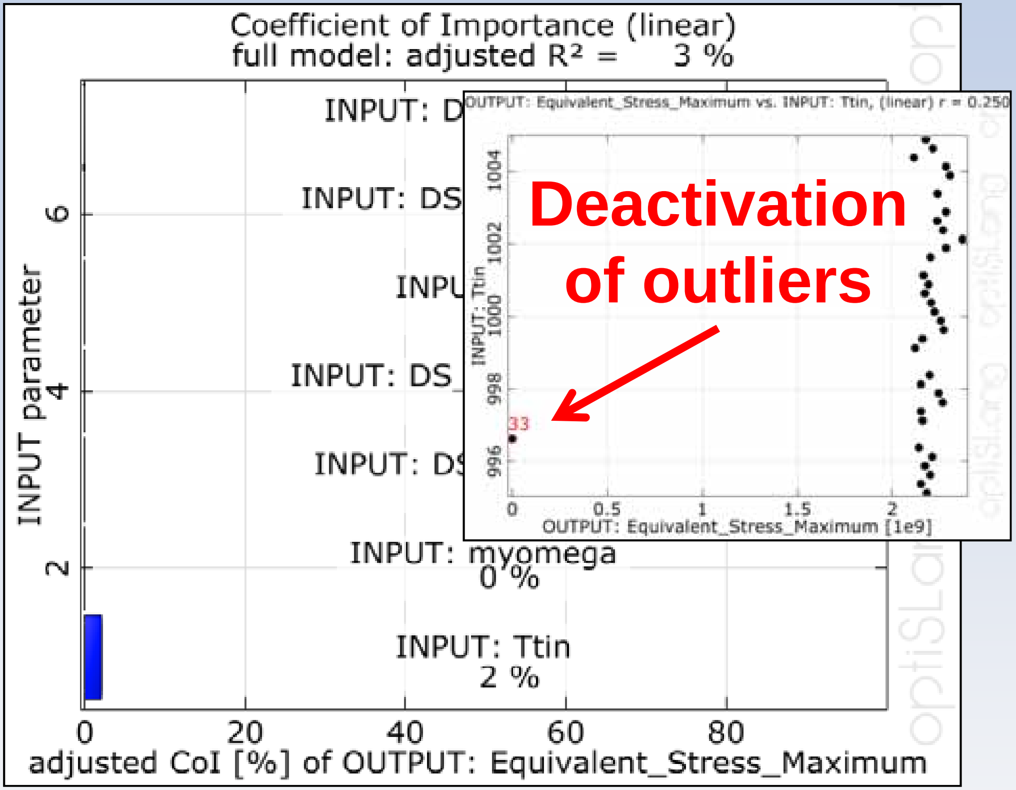
CoI=91%>80%

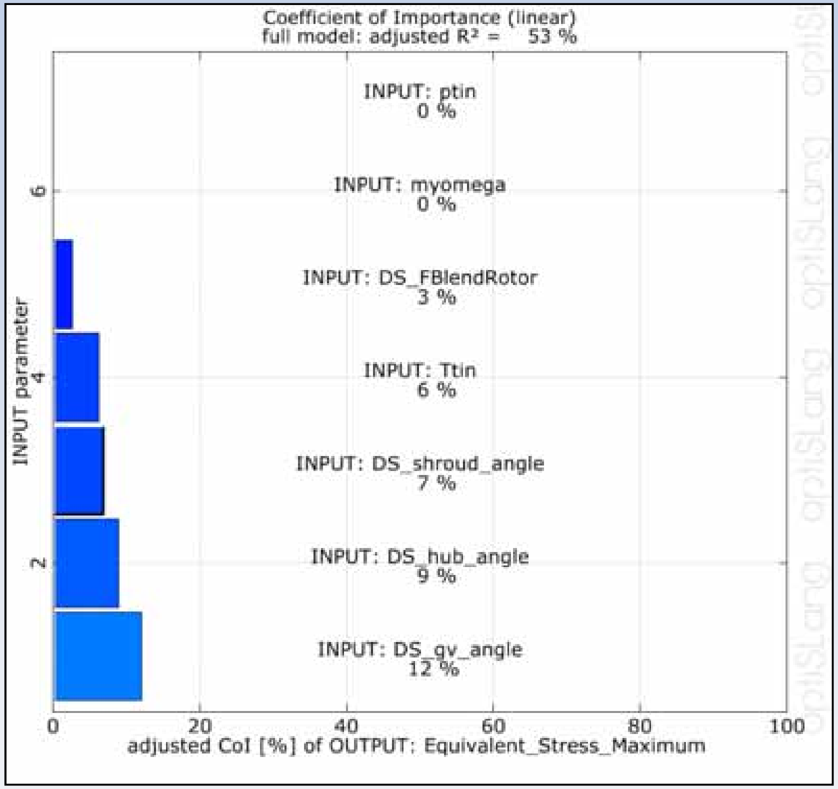






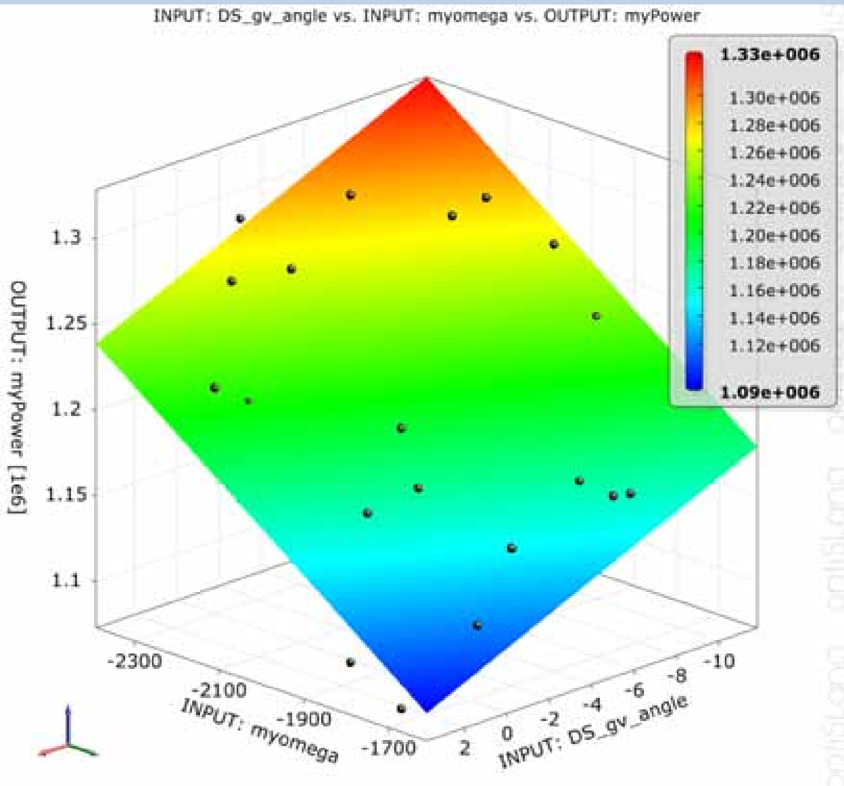
Coefficient of Importance, CoI





50% variance of the stress variation can be explained by the given n = 7 design variables

Meta-Model of Prognosis, MoP



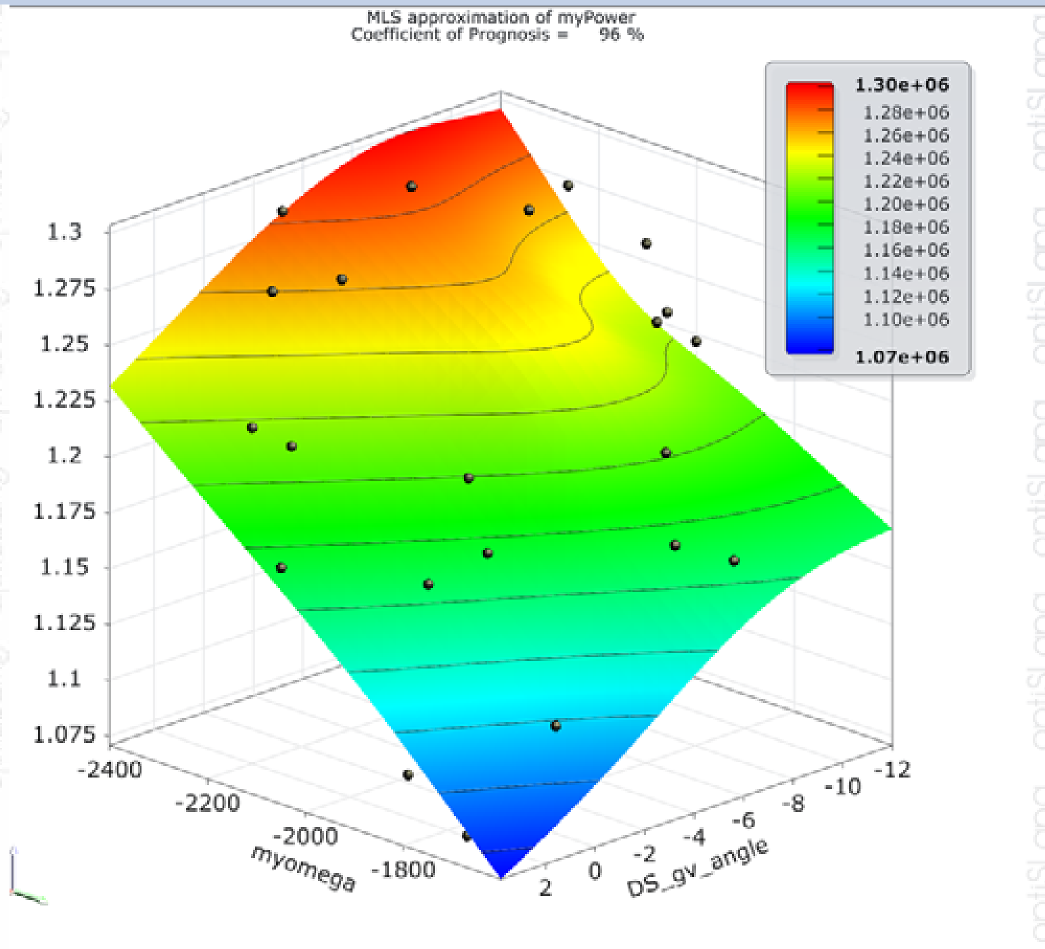
Linear regression z = a*x + b*y + c

coefficients:

a = -5740.83

b = -191.993

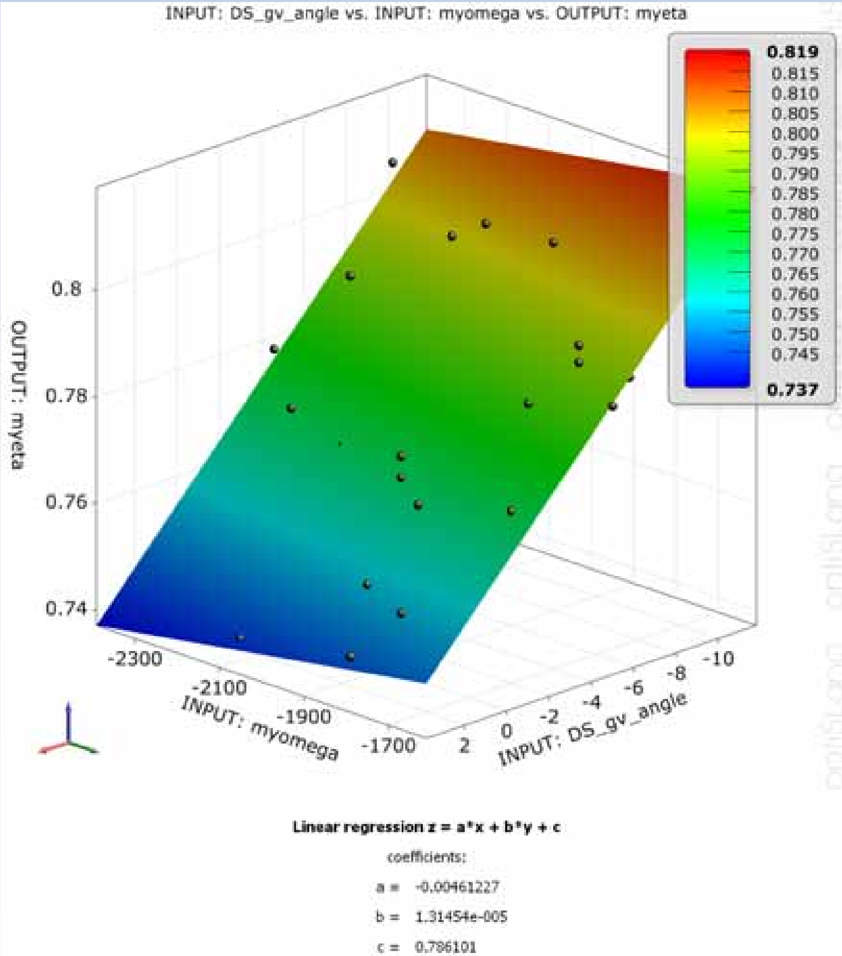
c = 801806

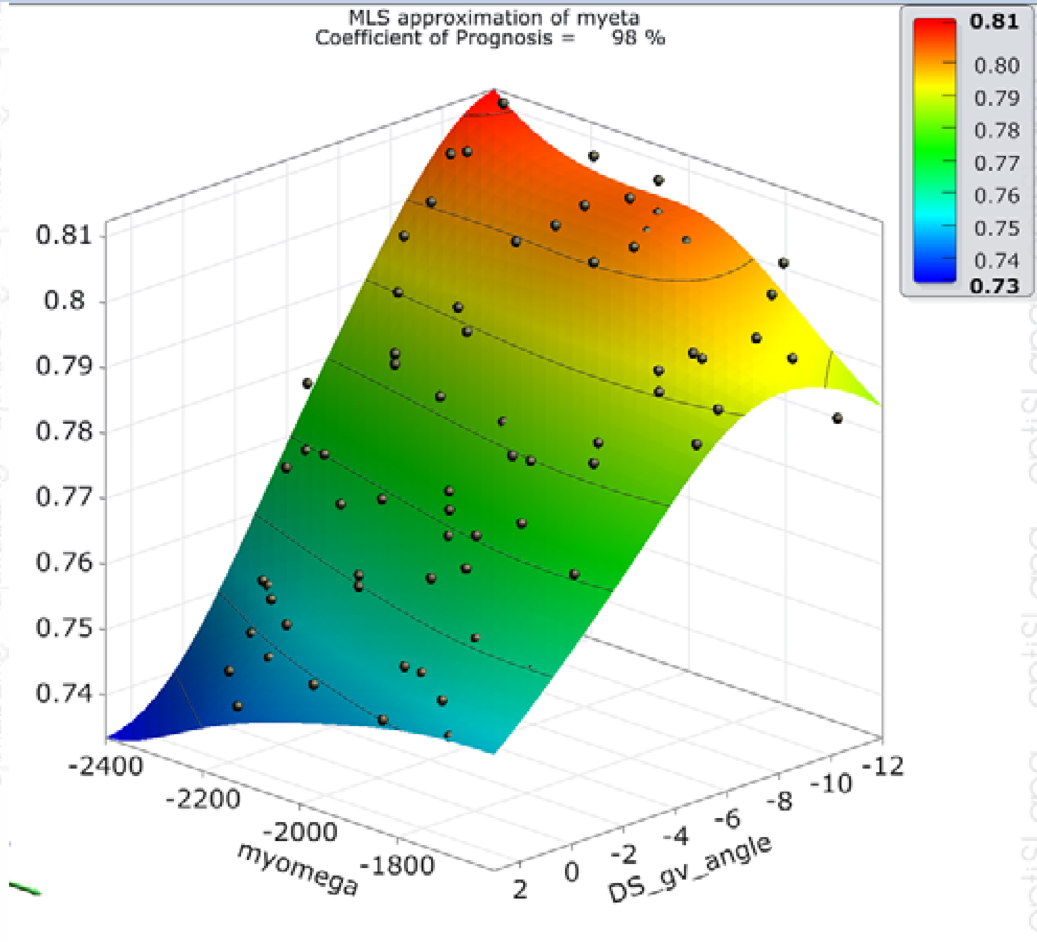


Response Surface
Output: Power

Meta-Model
Output: Power

Meta-Model of Prognosis, MoP

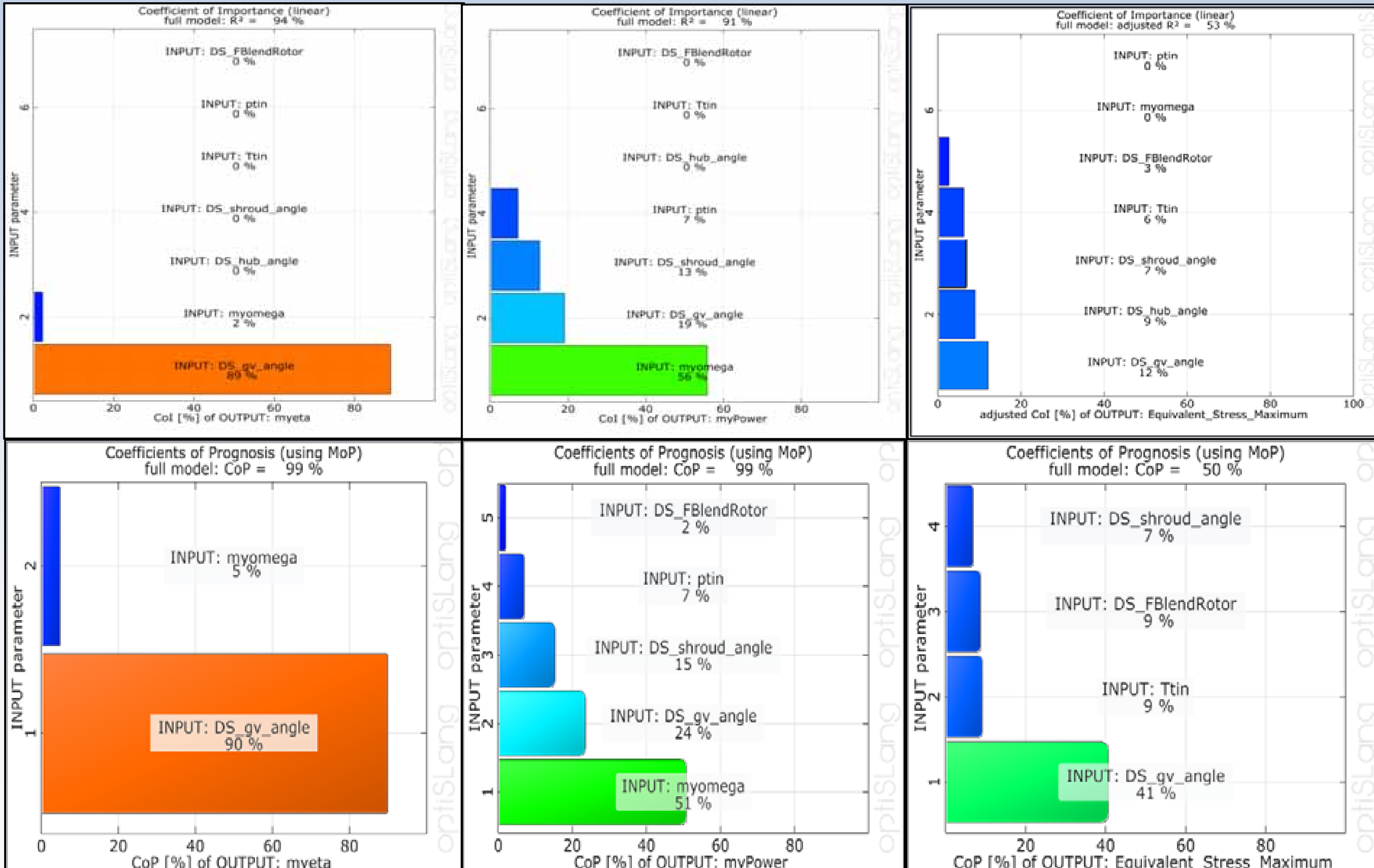




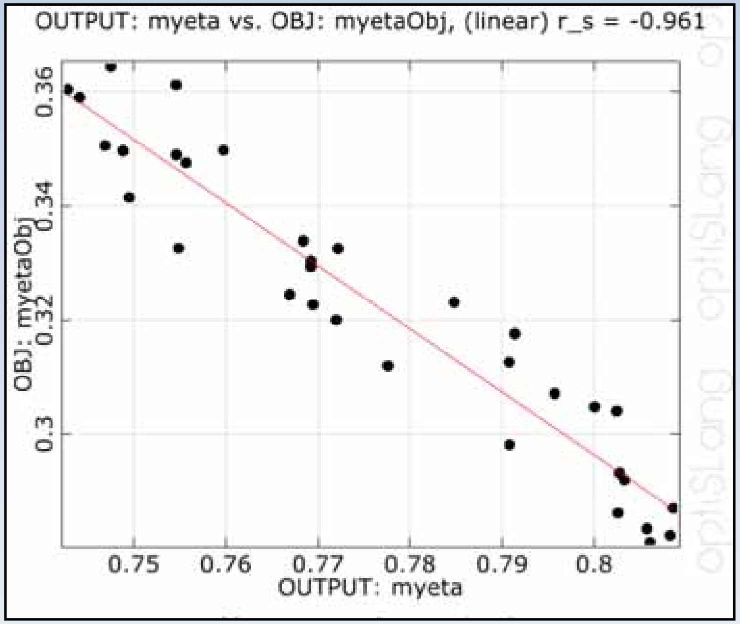
Response Surface
Output: Efficiency

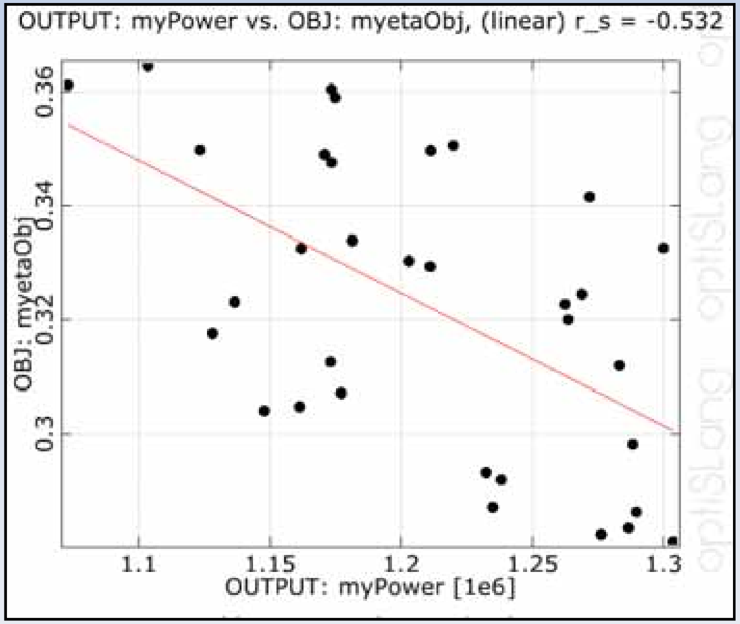
Meta-Model
Output: Efficiency

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



Objective Function

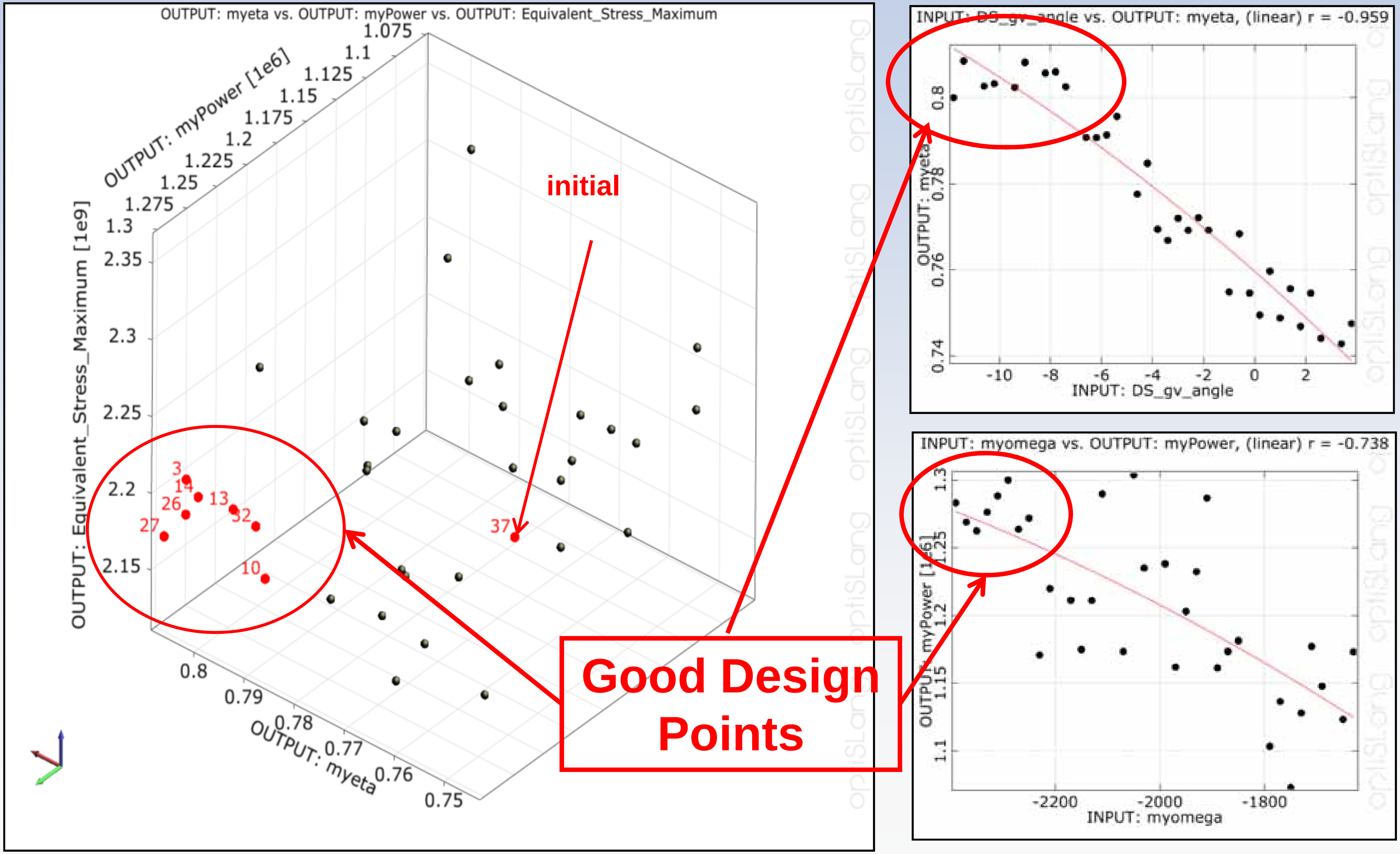




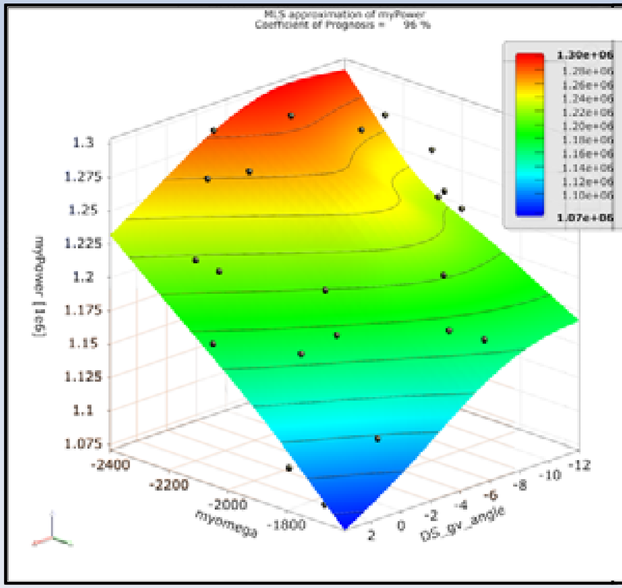
Target Function for Optimization:

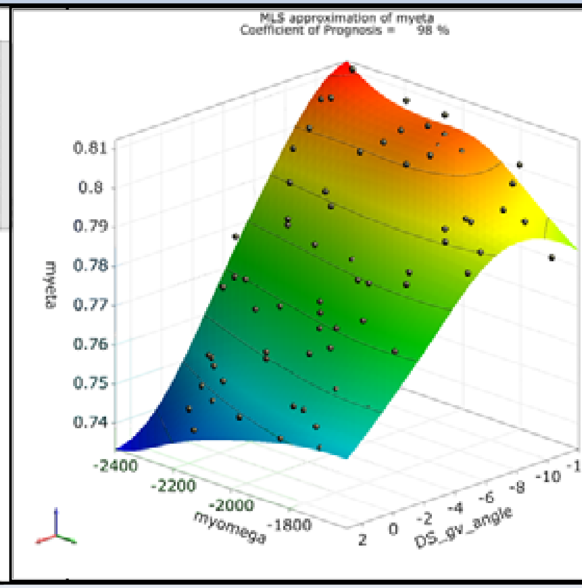
$$f_{\mathrm{Target}} = (1-\eta) + \frac{1}{4} \cdot \left(1 - \frac{P}{2[MW]}\right) \stackrel{!}{=} \min; \quad \sigma_{seqv} < \sigma_{Limit}$$

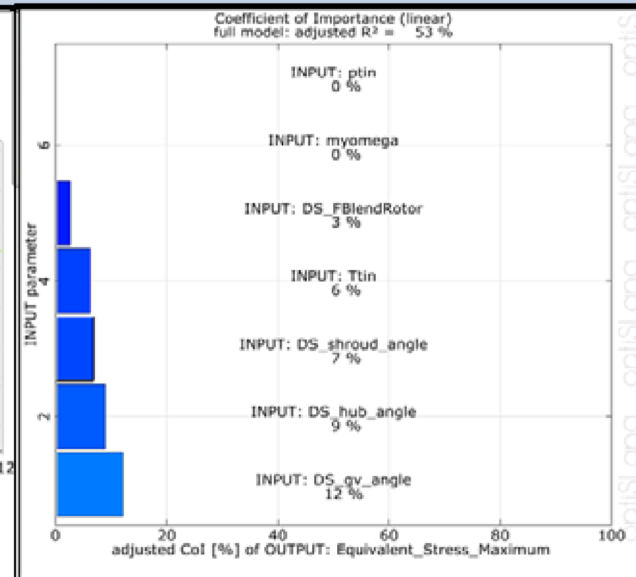
Anthill Plots Objective

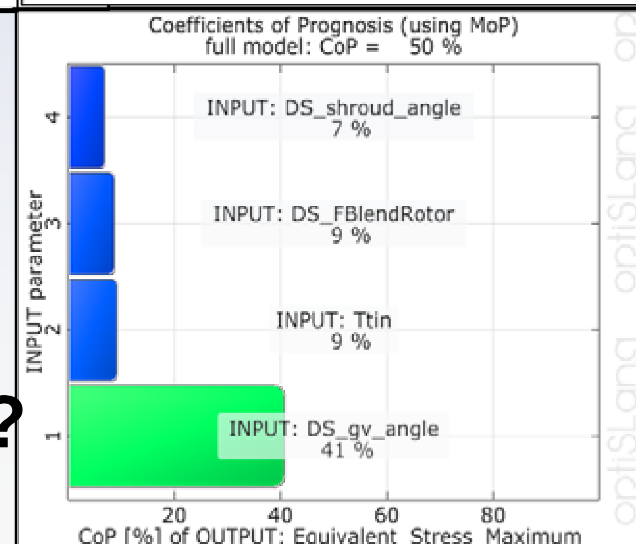


Conclusion Sensitivity Analysis

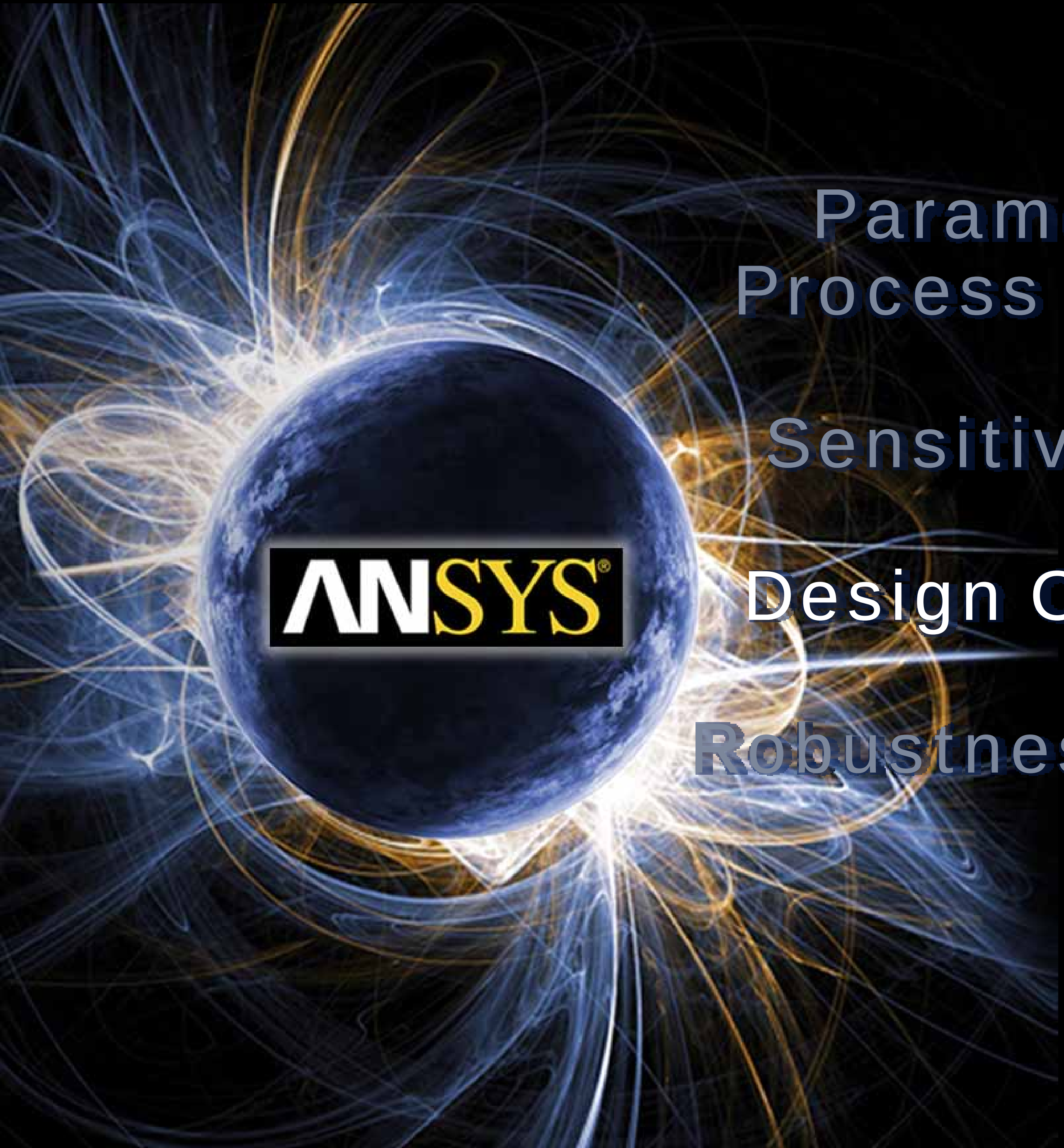








- **Is Sensitivity reliable, CoI?**
- **Is Sensitivity reliable, CoP?**
- **Is Sensitivity plausible, physics?**



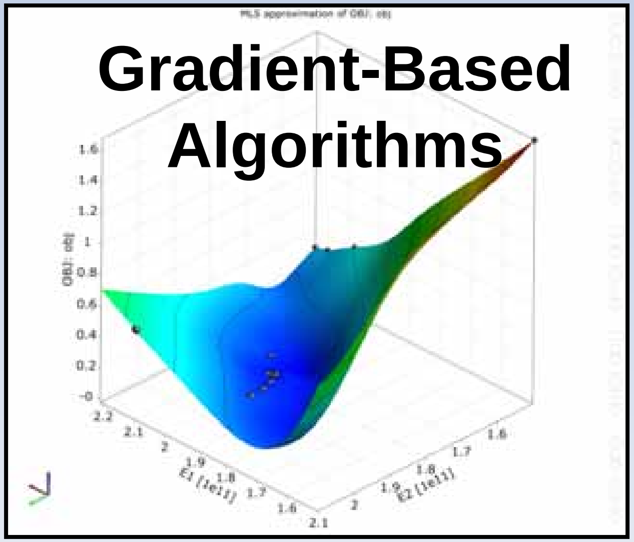
Parameterization
Process & Geometry

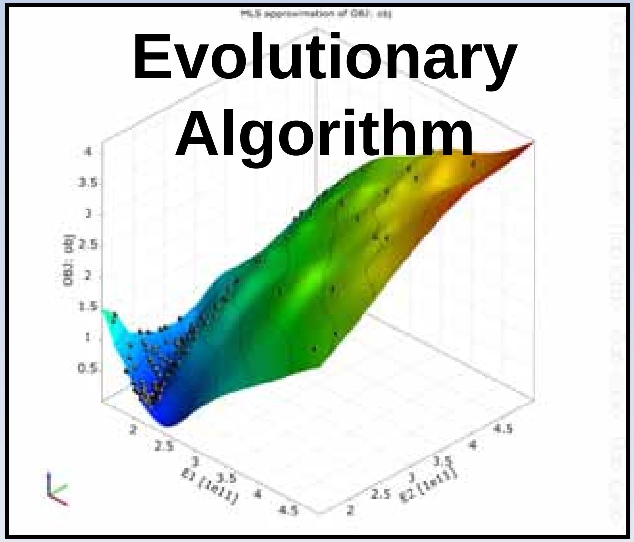
Sensitivity Analysis

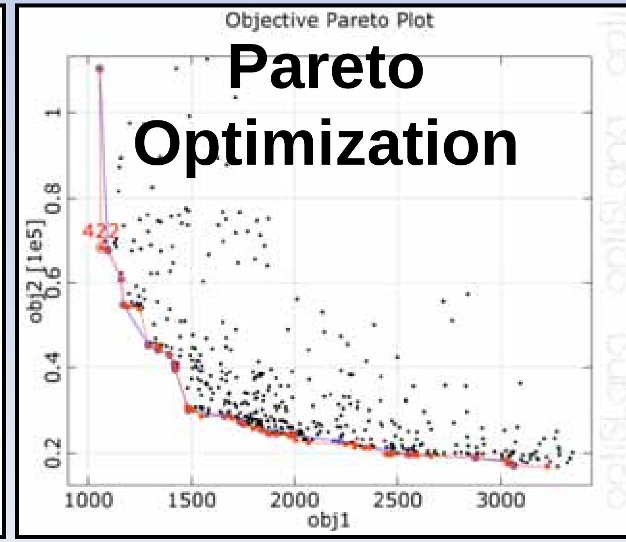
Design Optimization

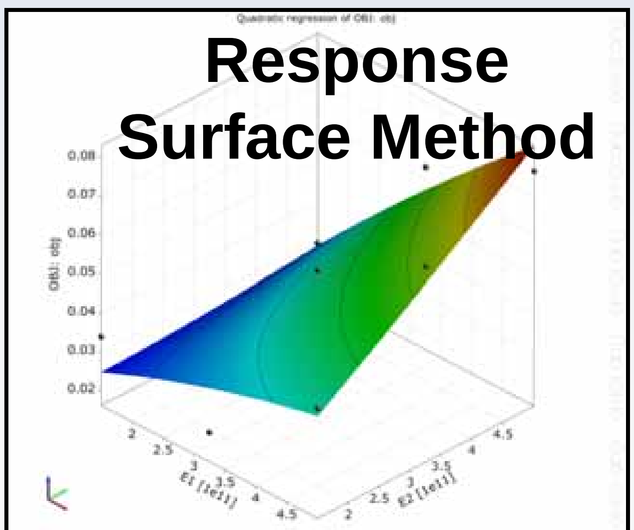
Robustness Evaluation

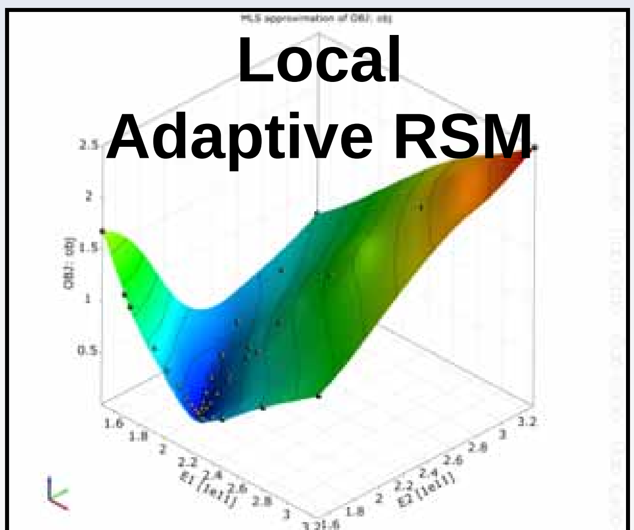
Design Optimization

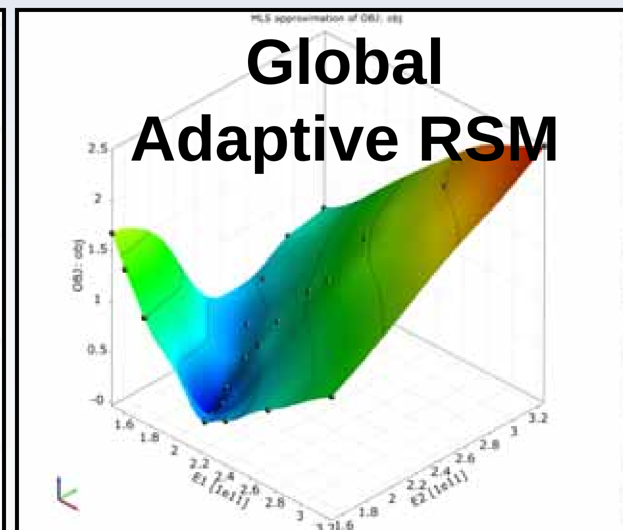












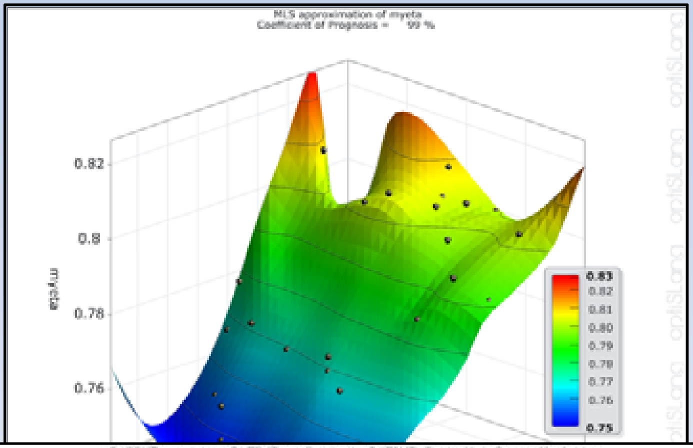
Optimization Strategy

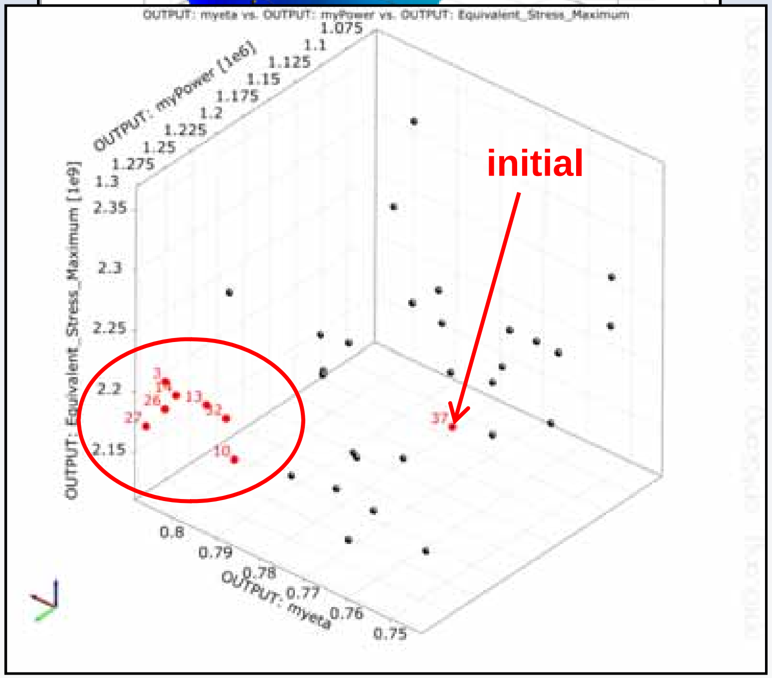
Sensitivity Analysis

- **Shows Potential**
- **Indicates multiple local optima**
- **No parameter reduction**

Strategy:

- **Global search, EA**
- **Start design(s) from SA**
- **Local improvement, ARSM**

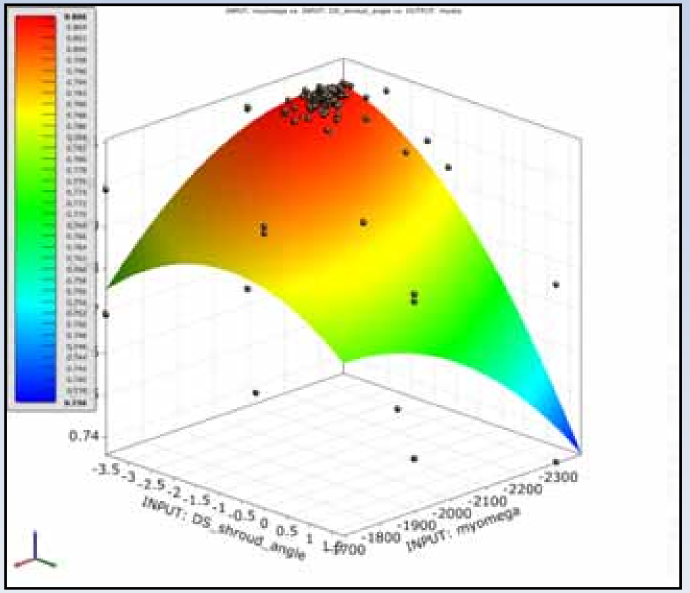




Outlook Strategy

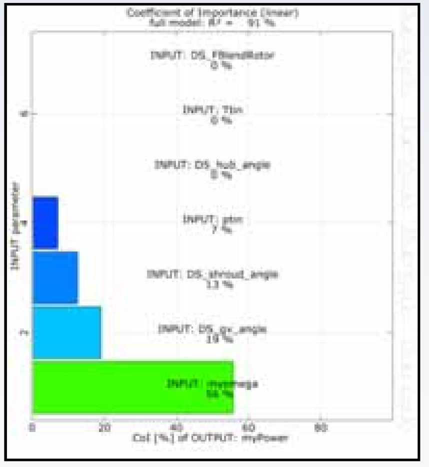
Sensitivity Analysis

- **Shows Potential**
- **Indicates global optimum**
- **Parameter reduction**



Strategy:

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

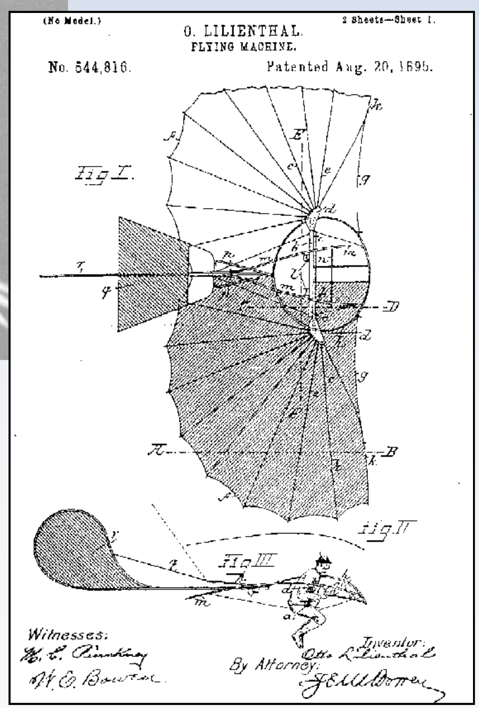


Evolutionary Algorithms (EA)

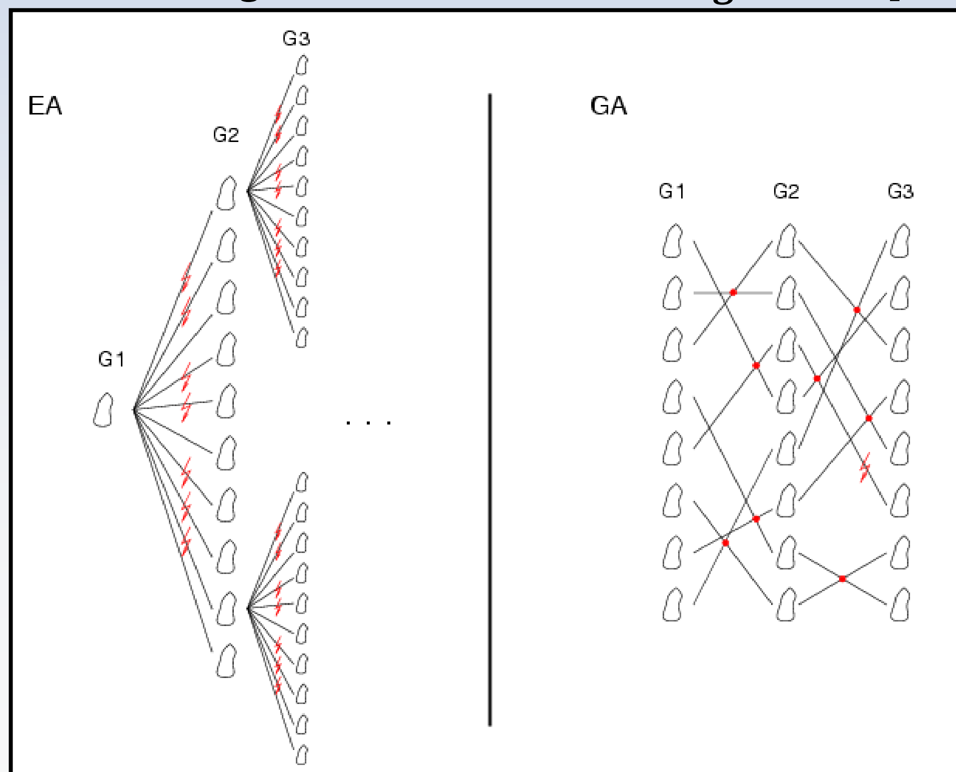
Optimization in Nature:

- Survival of the fittest

- Evolution due to mutation, recombination and selection

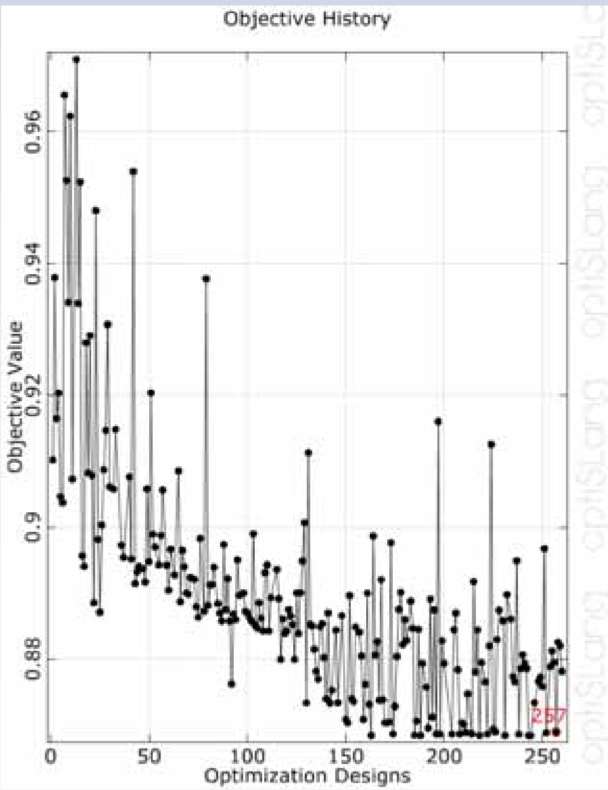


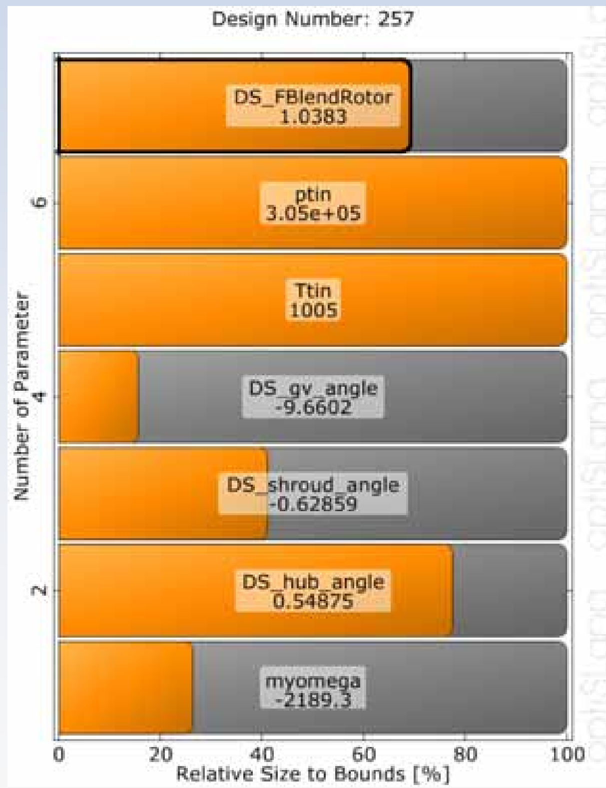
Evolution Algorithms [EA] **Genetic Algorithms [GA]**

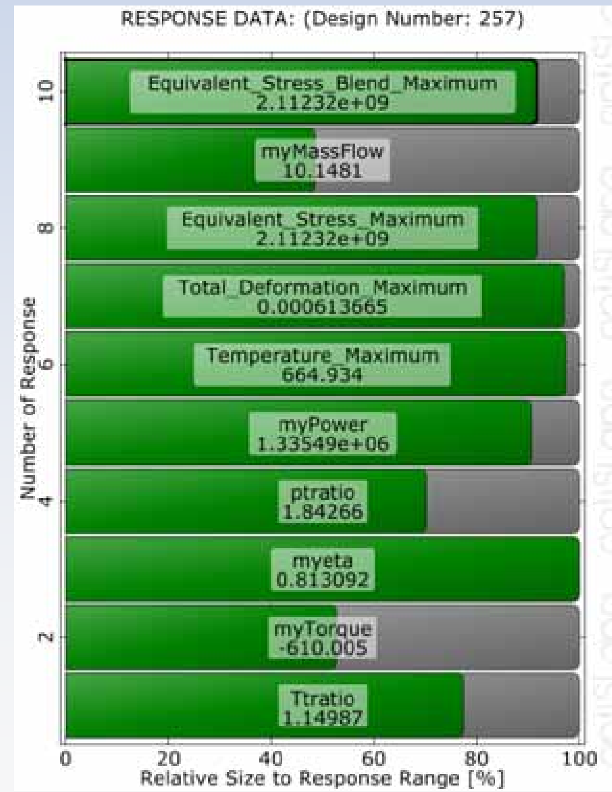


Evolutionary Algorithms (EA)

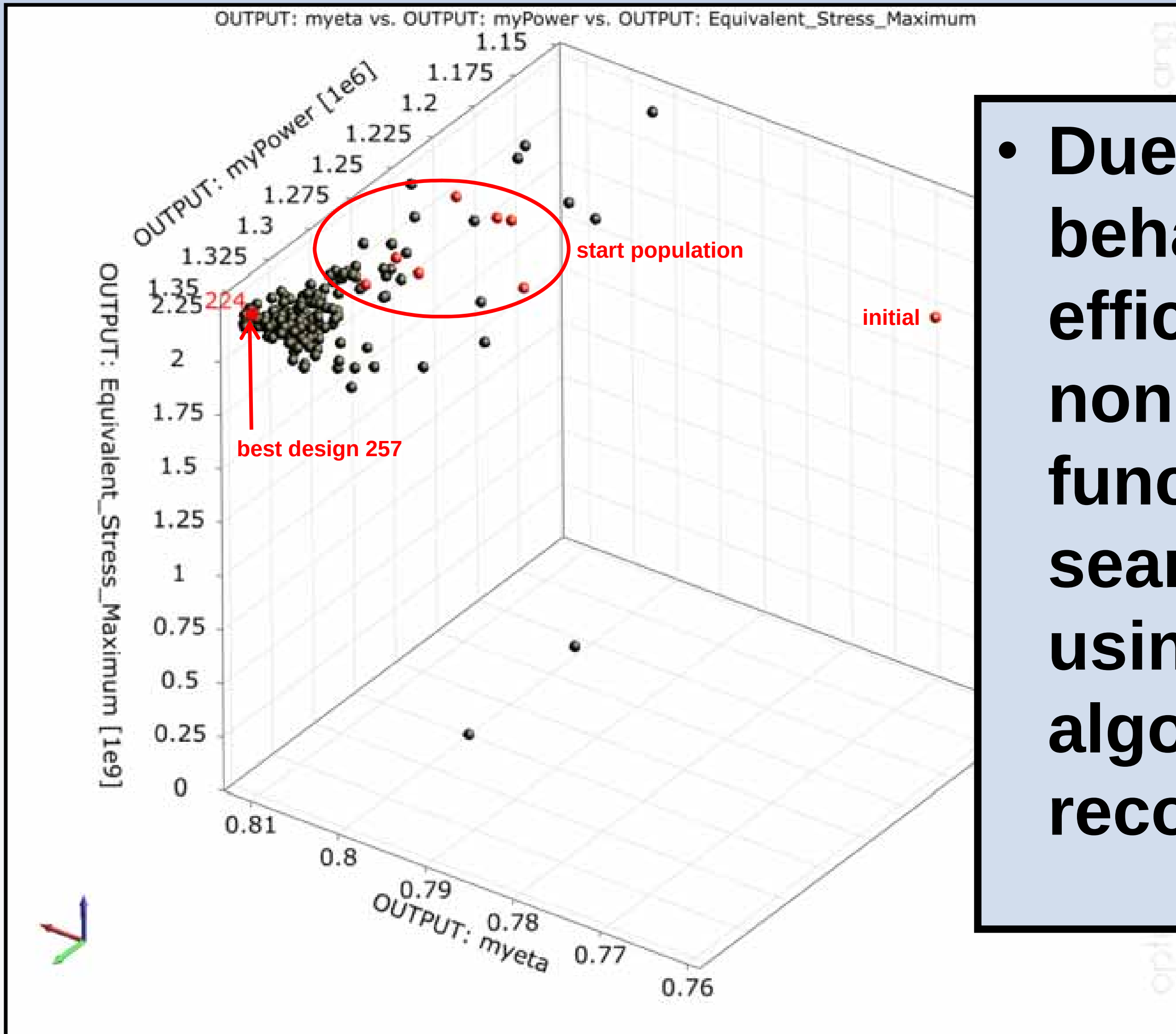
- **History of the Evolutionary Algorithm**





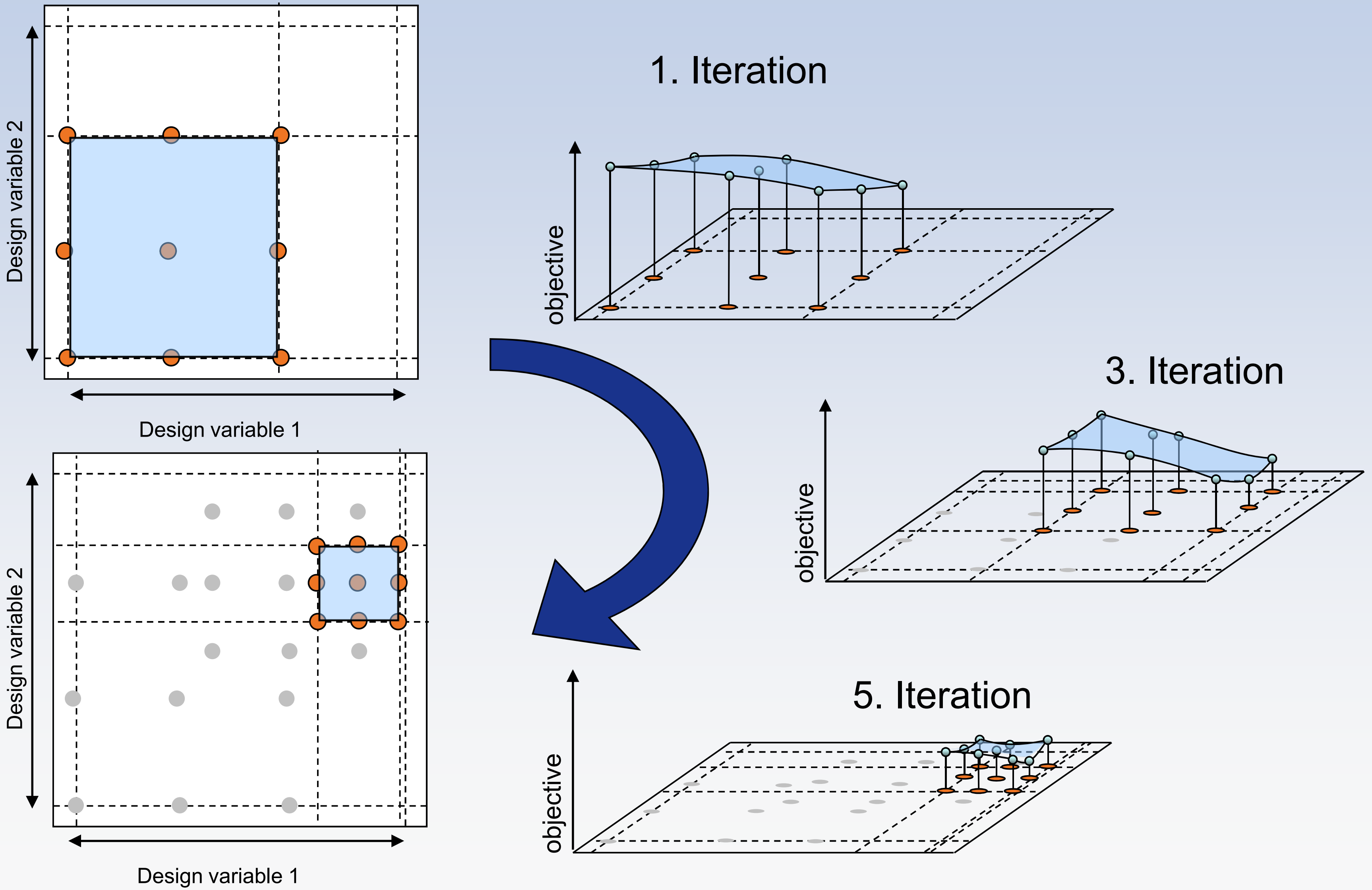


Evolutionary Algorithms (EA)

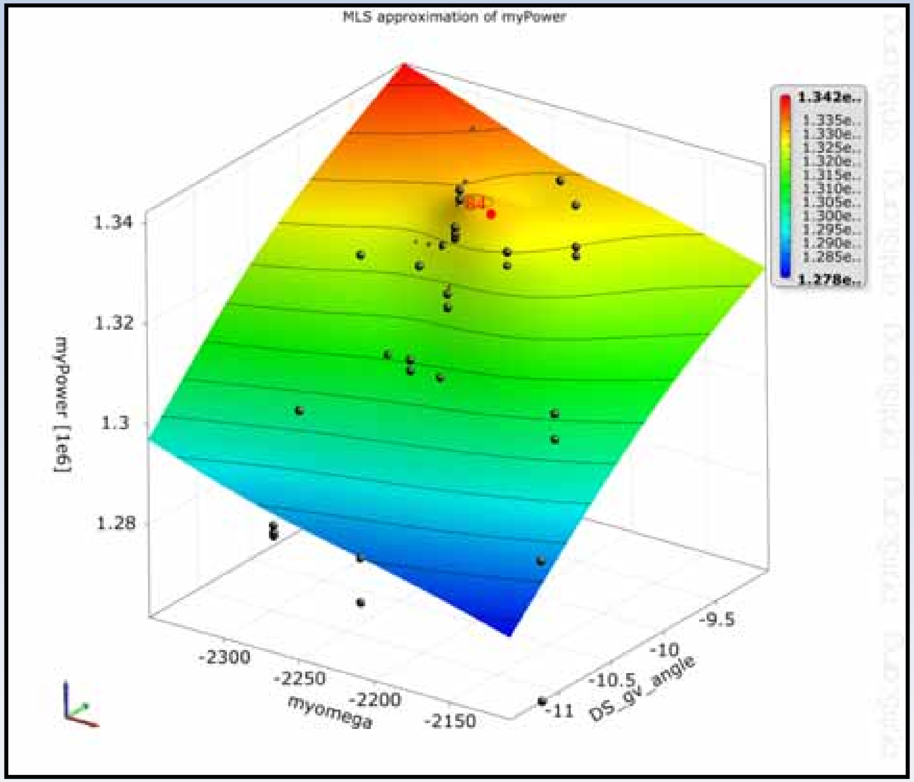


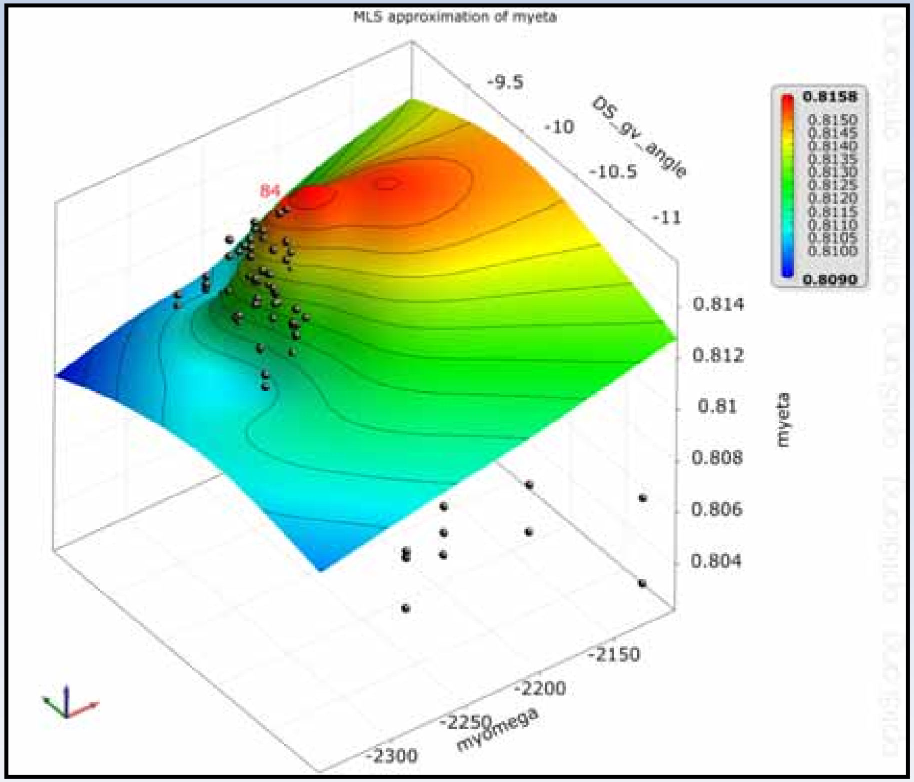
- **Due the non-convex behavior of the efficiency and nonlinear power function a global search strategy using genetic algorithm is recommended**

Adaptive Response Surface Methods (Local)



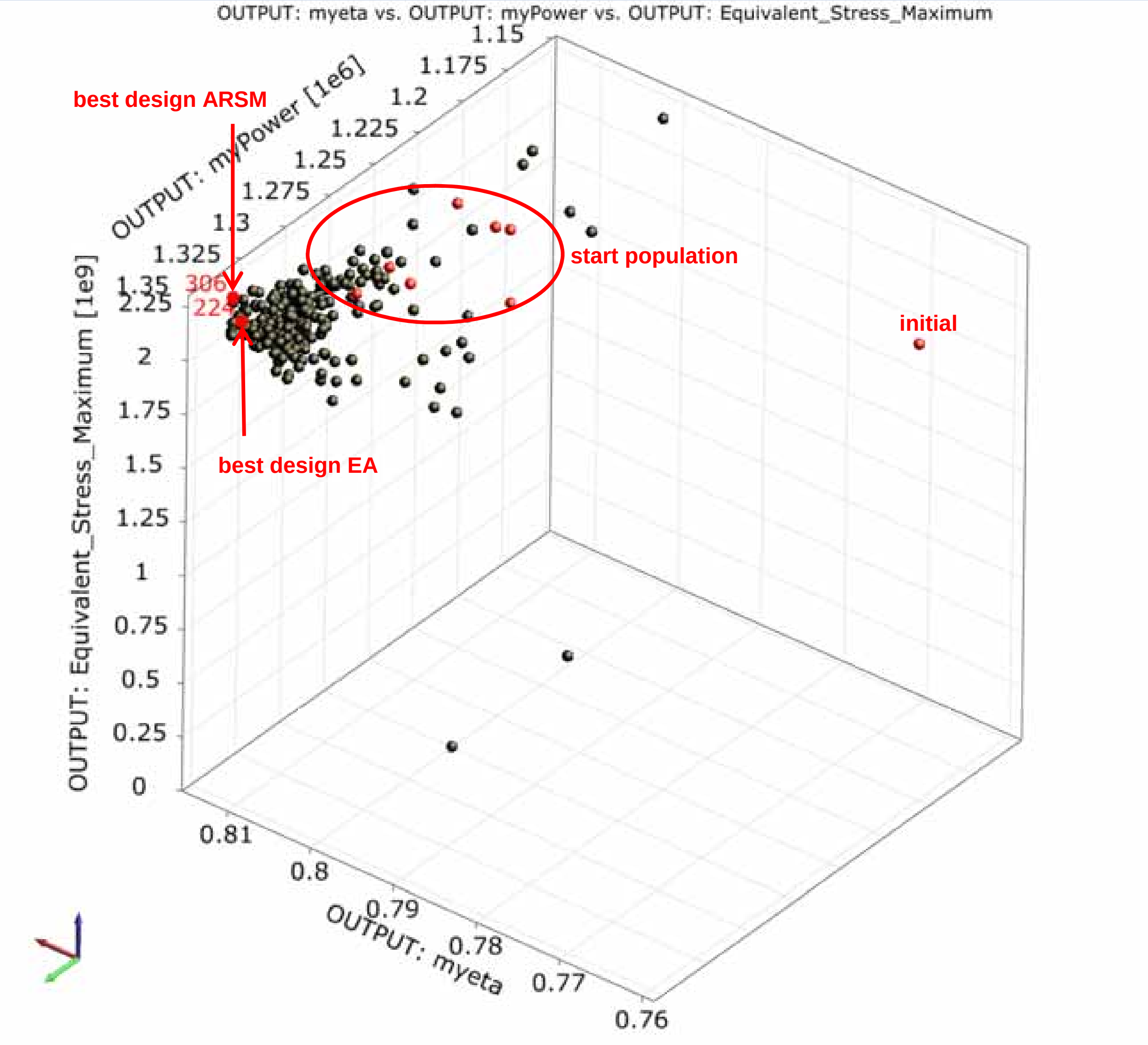
Adaptive Response Surface (ARSM)

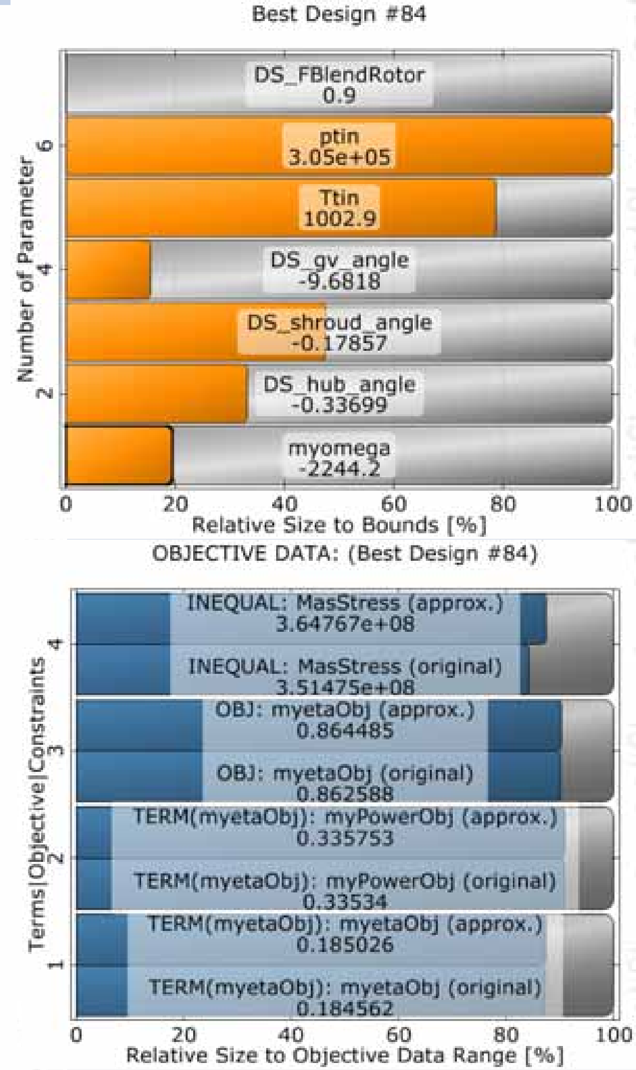




- **The ARSM does not provide differentiable and smooth problems; very efficient for n < 15 design parameters**
- **Starting solution is based on the best design of the EA**
- **The design space is reduced to 20% around start solution**

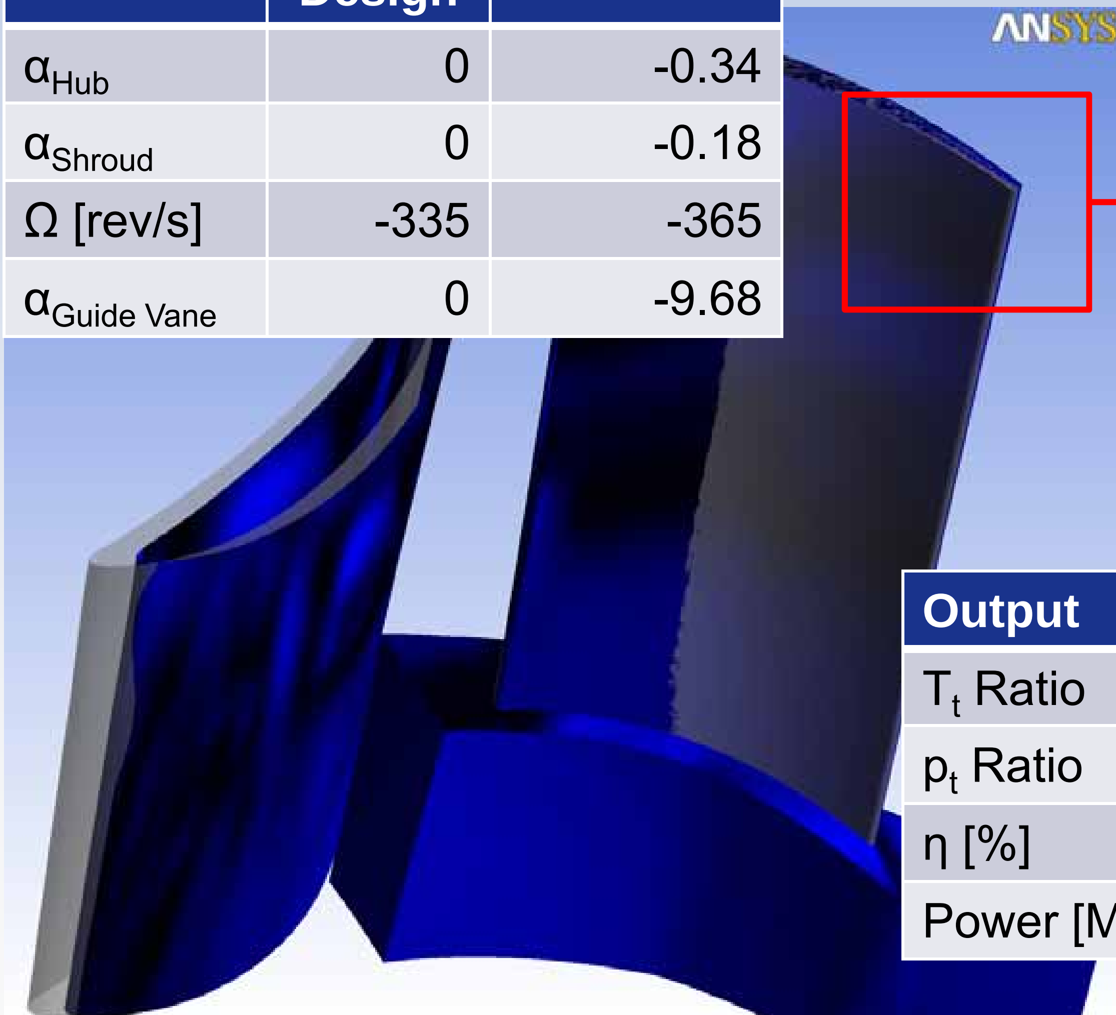
Adaptive Response Surface (ARSM)

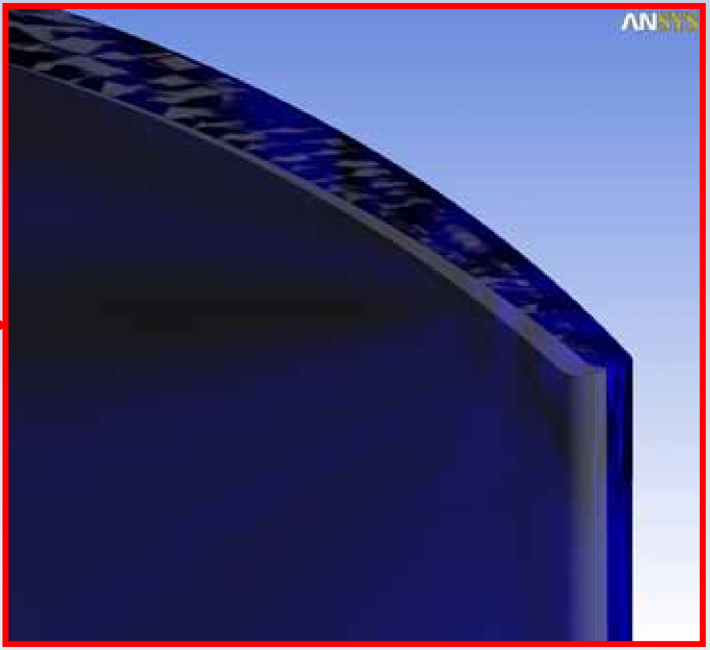




Initial vs. Optimized Design

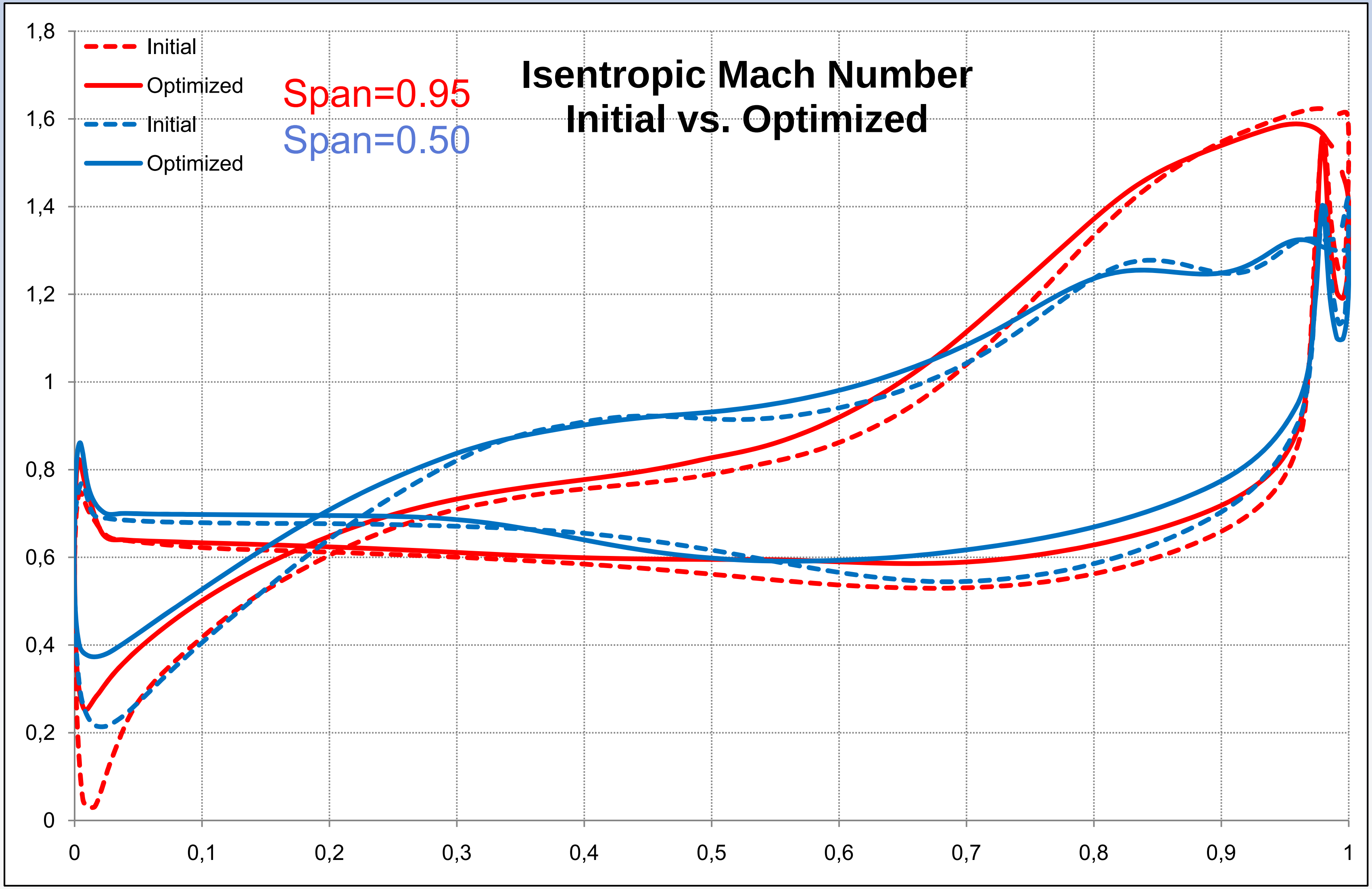
Input	Initial Design	Optimized
α_{Hub}	0	-0.34
α_{Shroud}	0	-0.18
Ω [rev/s]	-335	-365
$\alpha_{Guide\ Vane}$	0	-9.68





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

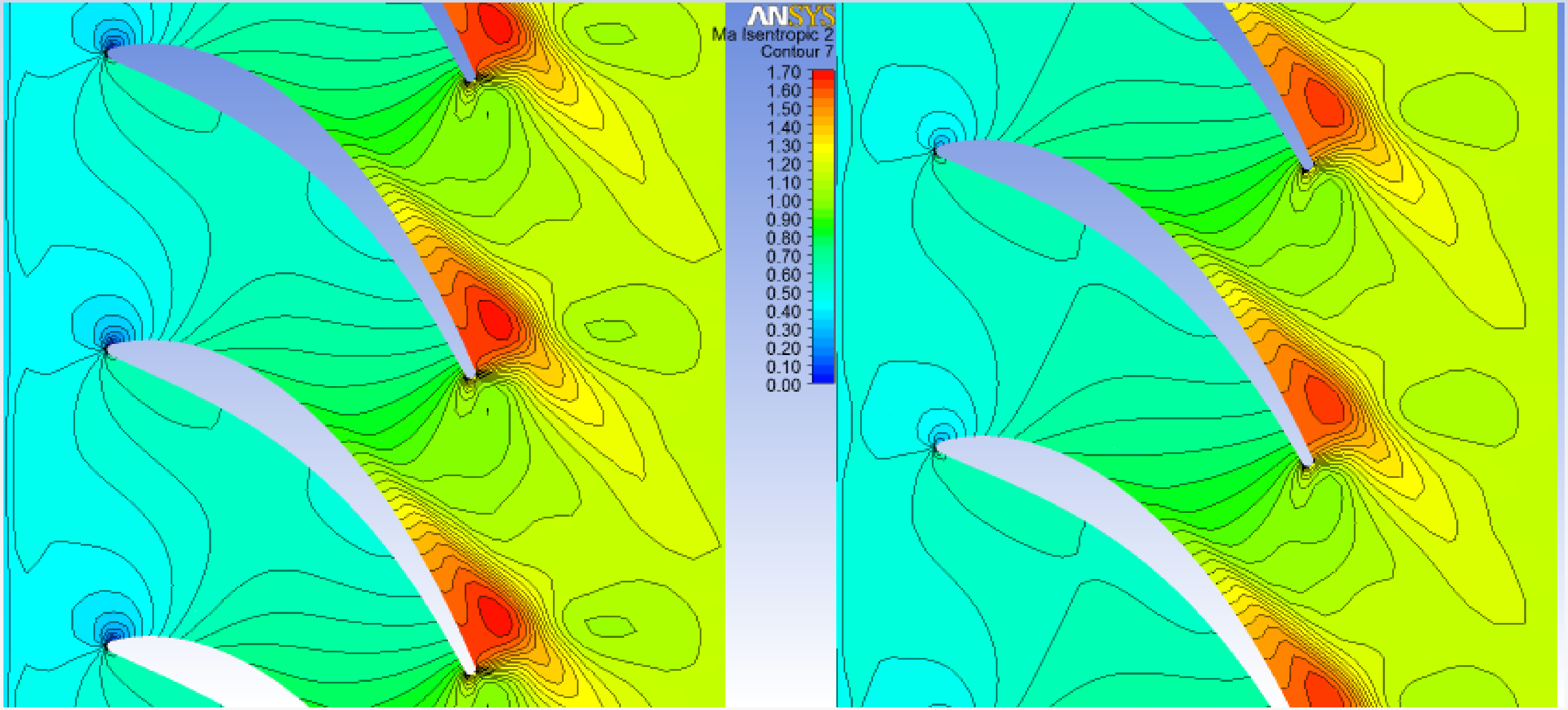
Initial vs. Optimized Design



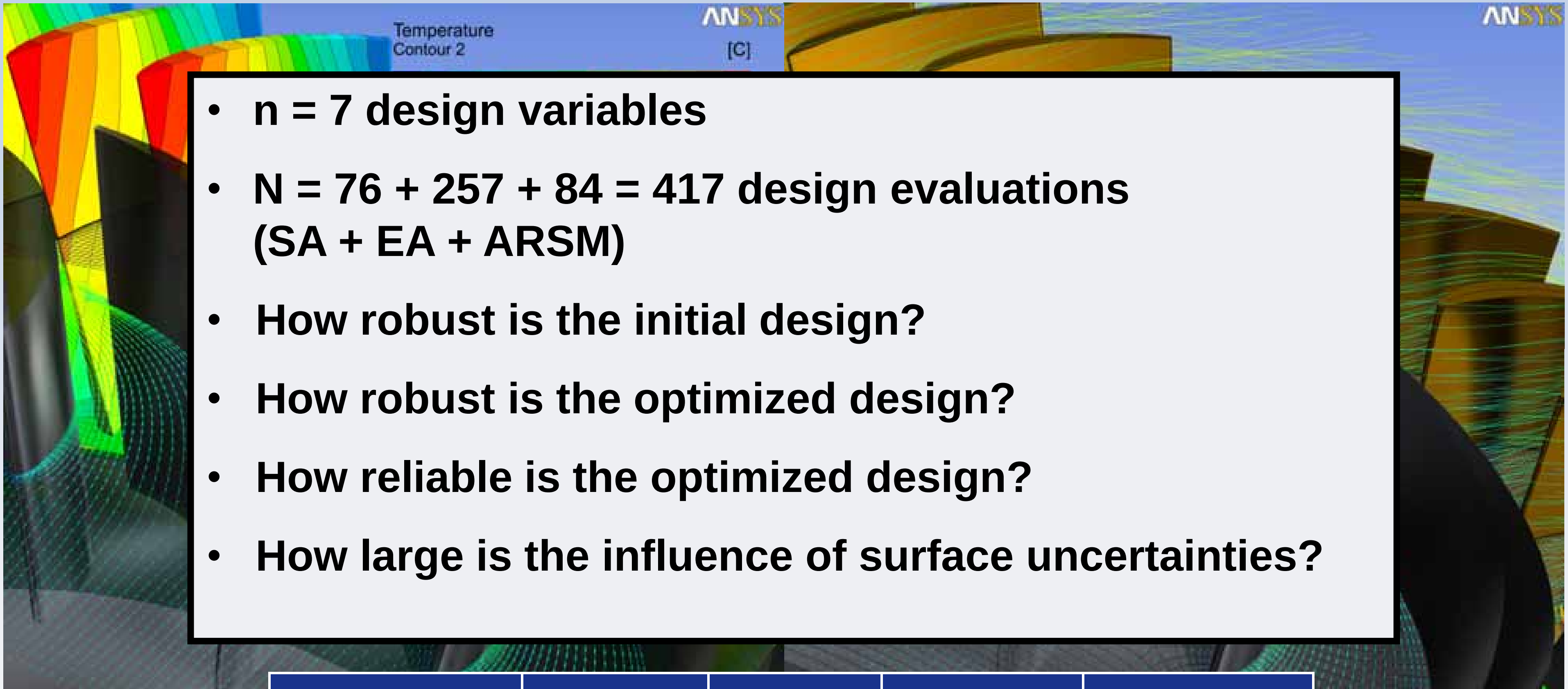
Initial vs. Optimized Design

Isotropic Mach Number

Initial | Rotor | Optimized

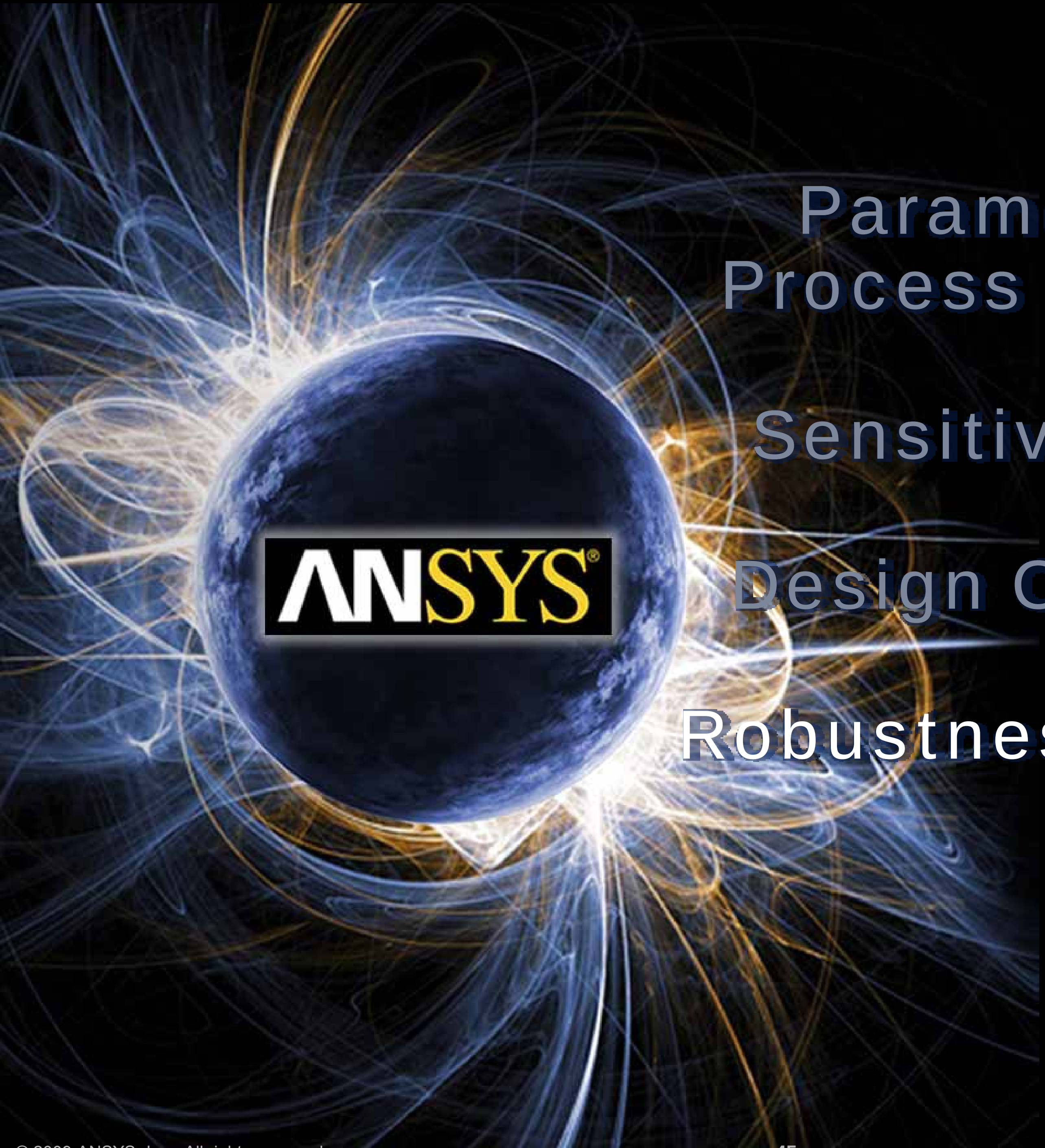


Initial vs. Optimized Design



- n = 7 design variables
- N = 76 + 257 + 84 = 417 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	SA	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

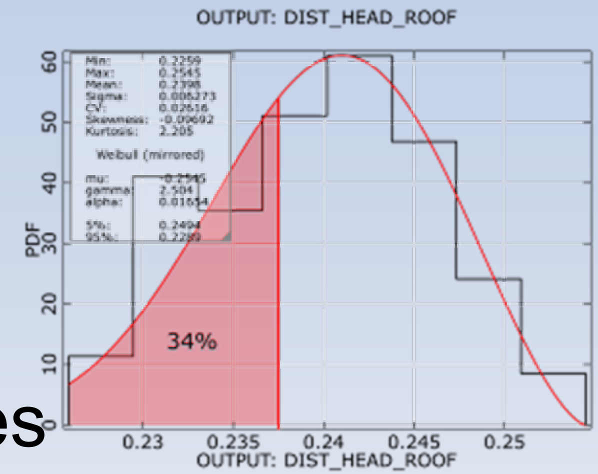
Sensitivity Analysis

Design Optimization

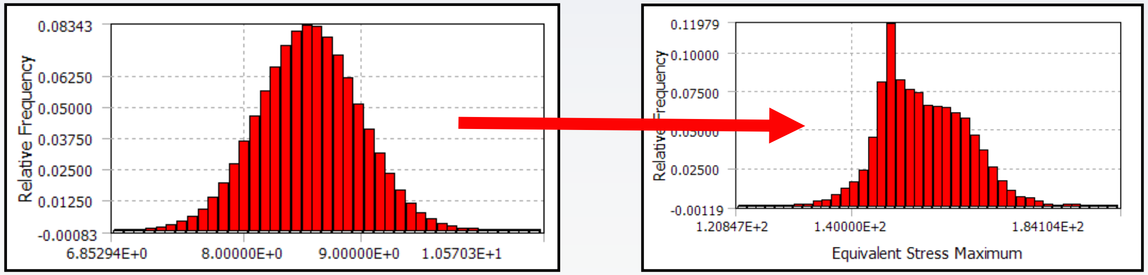
Robustness Evaluation

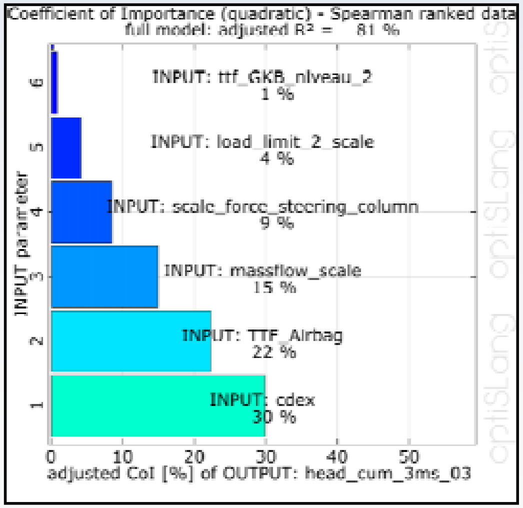
Robustness Evaluation

1. Scanning the Robust Space with optimized LHS, variation and correlation are investigated



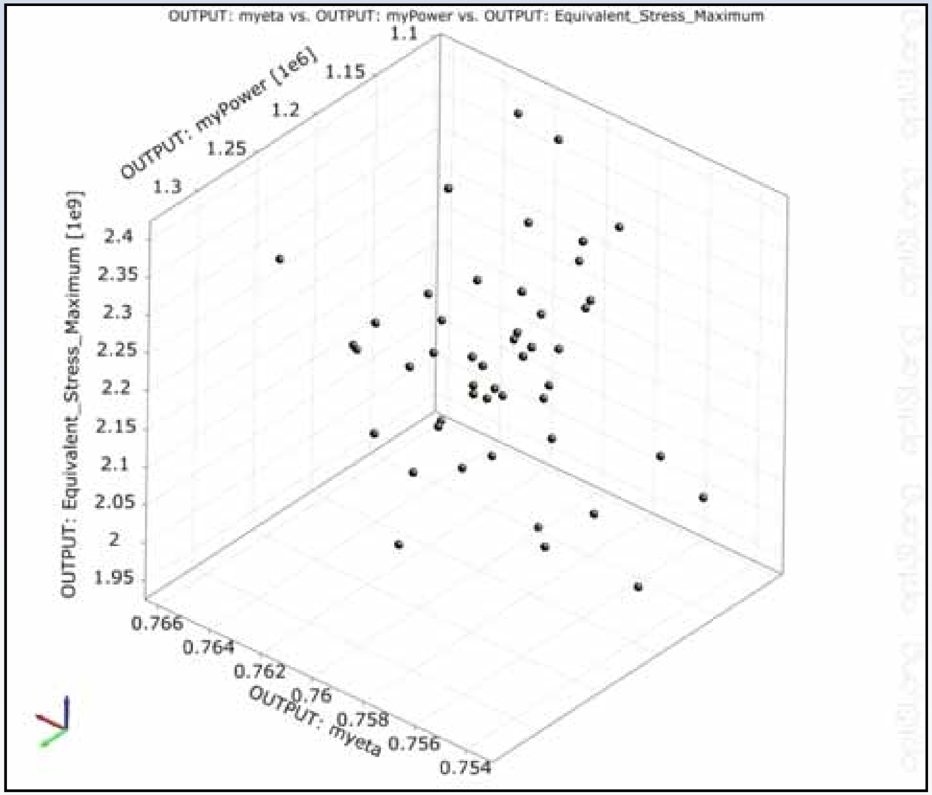
2. Identification of important variables
   - Check Variation of Robust Space
   - Check Histogram, limits, probabilities
   - Check Coefficient of Importance

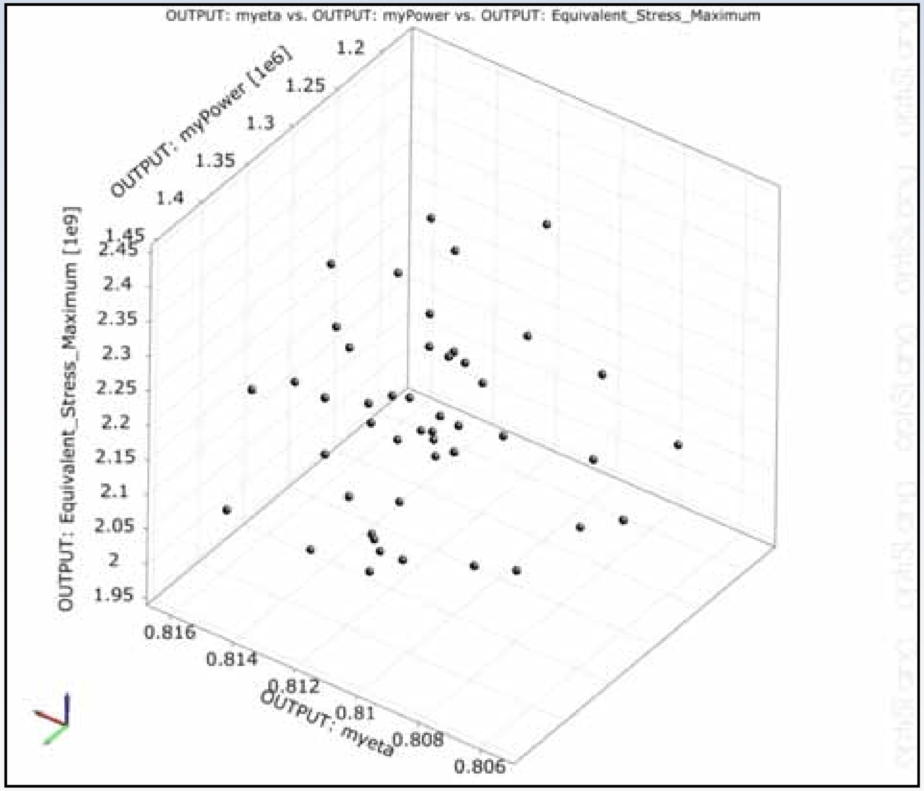




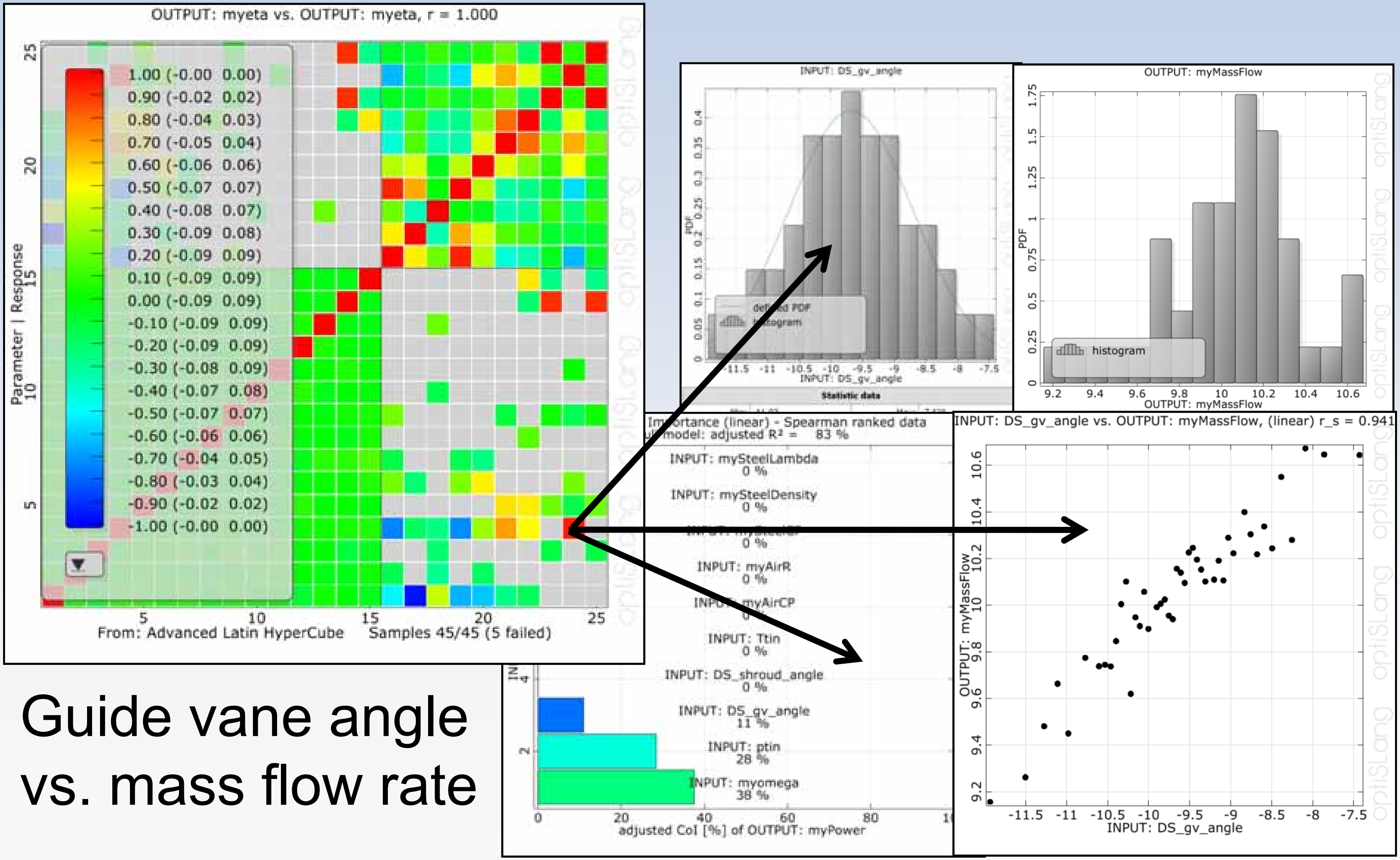
Variation of Robust Space

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





Correlation, CoI, Histogram



Guide vane angle vs. mass flow rate

Define Objective Limits

- **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

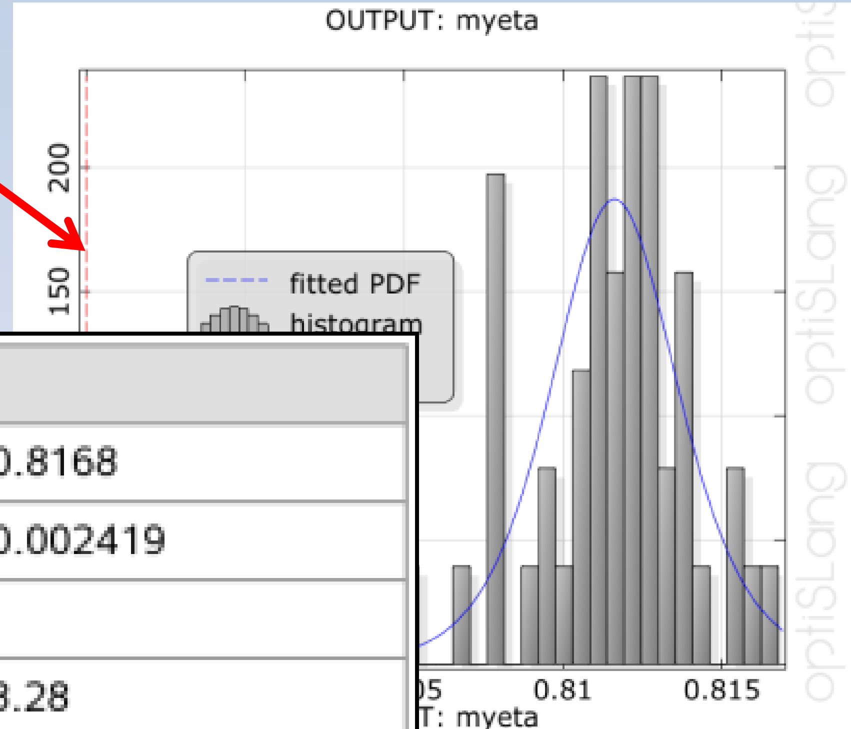
Opti | Robust | Output | Strings | Constraints | Objectives

#	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

Evaluation of Histogram

Limit for Variable

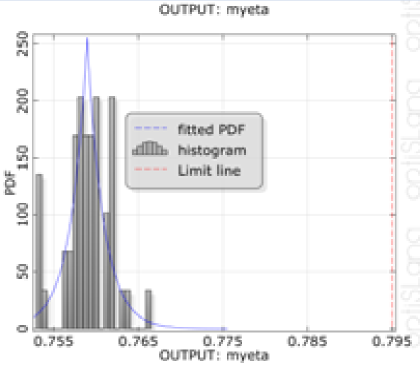


Statistic data			
Min:	0.8049	Max:	0.8168
Mean:	0.8116	Sigma:	0.002419
CV:	0.00298		
Skewness:	-0.4368	Kurtosis:	3.28
Fitted PDF: Logistic			
Mean:	0.8116	Sigma:	0.002419
Limit x = 0.795			
P_rel =	0	P_fit =	3.87374e-06

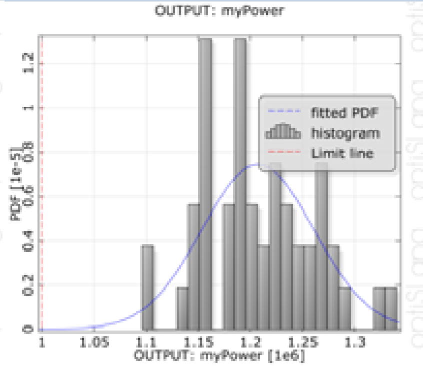
Max: 0.8168
Sigma: 0.002419
Kurtosis: 3.28
Sigma: 0.002419
Limit x = 0.795
P_rel = 0 P_fit = 3.87374e-06

Evaluation of Histogram

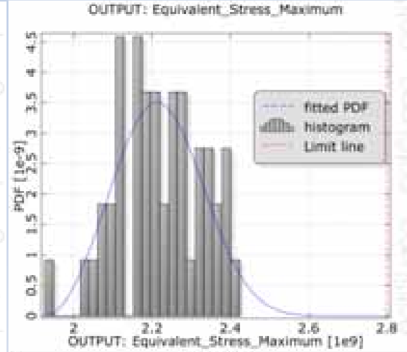
Non-robust initial design



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

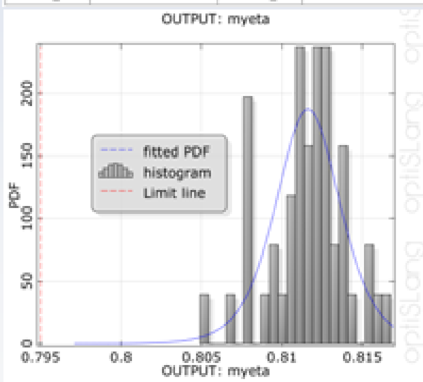


Statistic data			
Min:	1.096e+06	Max:	1.341e+06
Mean:	1.207e+06	Sigma:	5.364e+04
CV:	0.04444		
Skewness:	0.2879	Kurtosis:	2.766
Fitted PDF: Normal			
Mean:	1.207e+06	Sigma:	5.364e+04
Limit x = 1e+06			
P_rel =	0	P_fit =	5.67009e-05

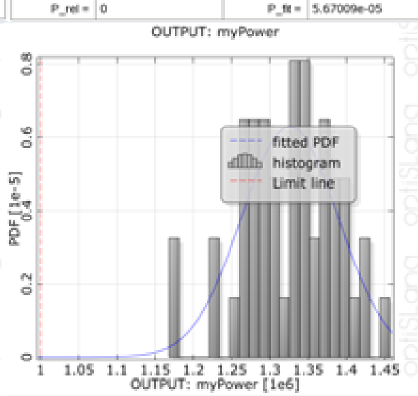


Statistic data			
Min:	1.926e+09	Max:	2.424e+09
Mean:	2.221e+09	Sigma:	1.086e+08
CV:	0.04892		
Skewness:	-0.2418	Kurtosis:	2.725
Fitted PDF: Extreme Typ III (Max) Weibull			
Mean:	2.221e+09	Sigma:	1.086e+08
Lower cut:	1.926e+09		
Limit x = 2.8e+09			
P_rel =	1	P_fit =	1

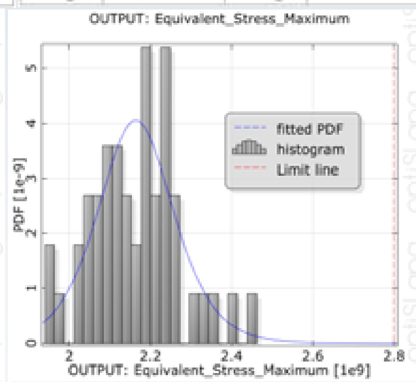
Robust optimized design up to a sigma level of 4.5



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



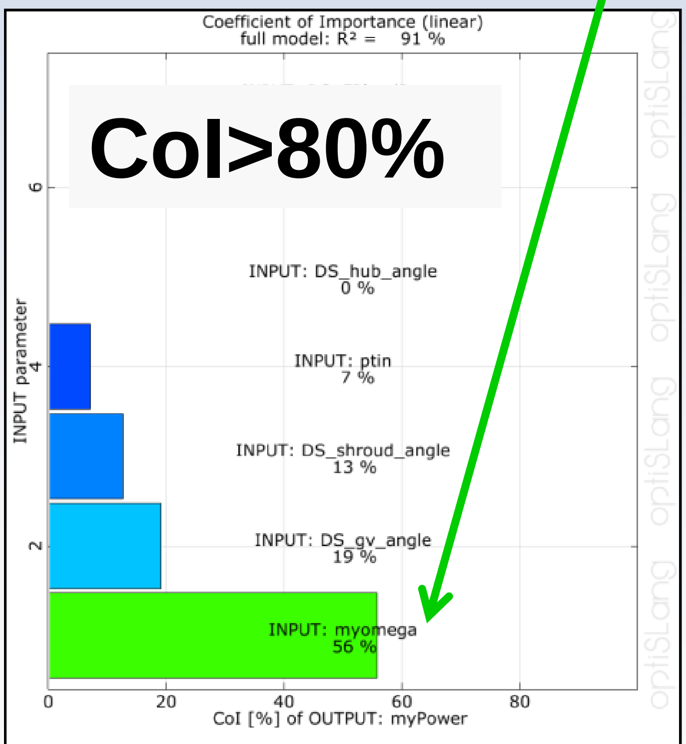
Statistic data			
Min:	1.168e+06	Max:	1.457e+06
Mean:	1.326e+06	Sigma:	6.335e+04
CV:	0.04776		
Skewness:	-0.3664	Kurtosis:	2.825
Fitted PDF: Normal			
Mean:	1.326e+06	Sigma:	6.335e+04
Limit x = 1e+06			
P_rel =	0	P_fit =	1.3062e-07

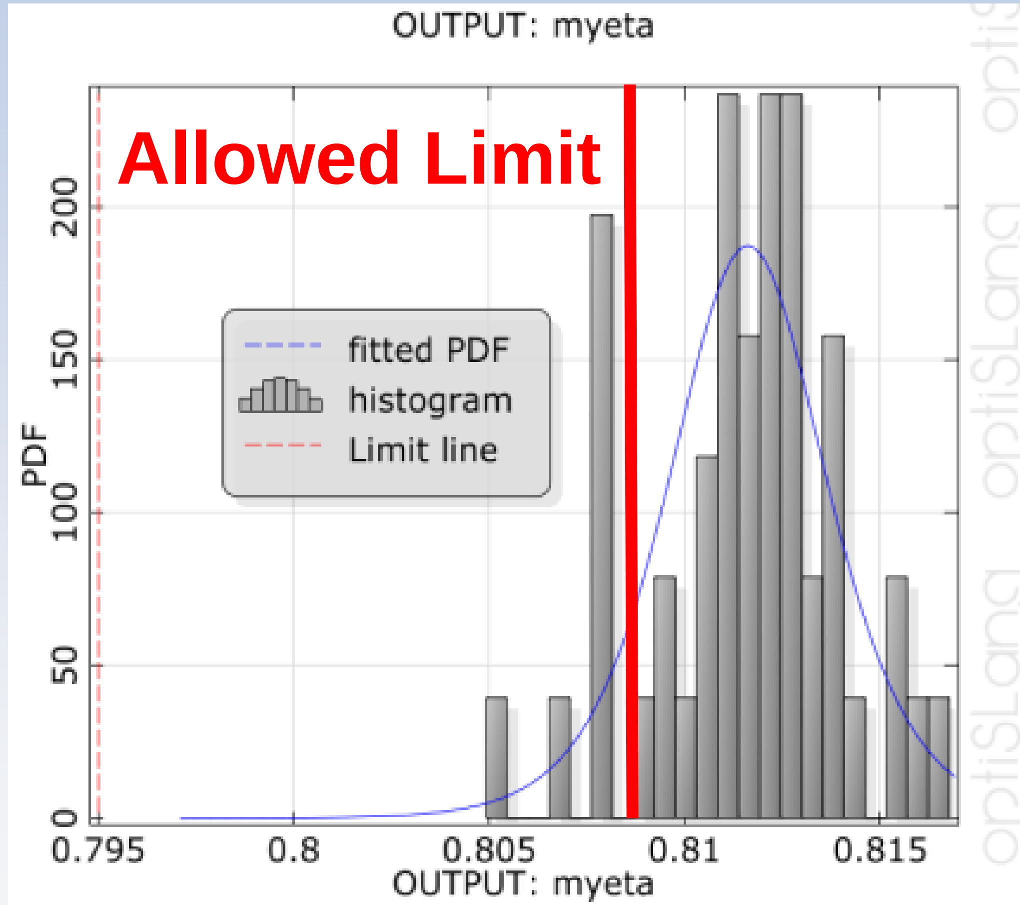


Statistic data			
Min:	1.94e+09	Max:	2.462e+09
Mean:	2.164e+09	Sigma:	1.118e+08
CV:	0.05165		
Skewness:	0.3229	Kurtosis:	3.244
Fitted PDF: Logistic			
Mean:	2.164e+09	Sigma:	1.118e+08
Limit x = 2.8e+09			
P_rel =	1	P_fit =	0.999967

Conclusion Robustness Evaluation

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





Parameterization
Process & Geometry

Sensitivity Analysis

Design Optimization

Robustness Evaluation

Summary

Summary

- **Workbench supports full Workflow**
  - Geometry, Meshing, Simulation, Post-Processing
- **Multi Physics support**
- **Parametric Workflow management**
- **Automatic and embedded solution procedure**
- **Sensitivity Analysis**
- **Design Optimization**
- **Robustness Evaluation**