

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

The ANSYS logo is centered on a dark blue sphere that resembles the Earth. The sphere is surrounded by a complex, glowing network of blue and orange lines, suggesting a fluid flow or simulation. The ANSYS logo itself is in white and yellow text on a black rectangular background.

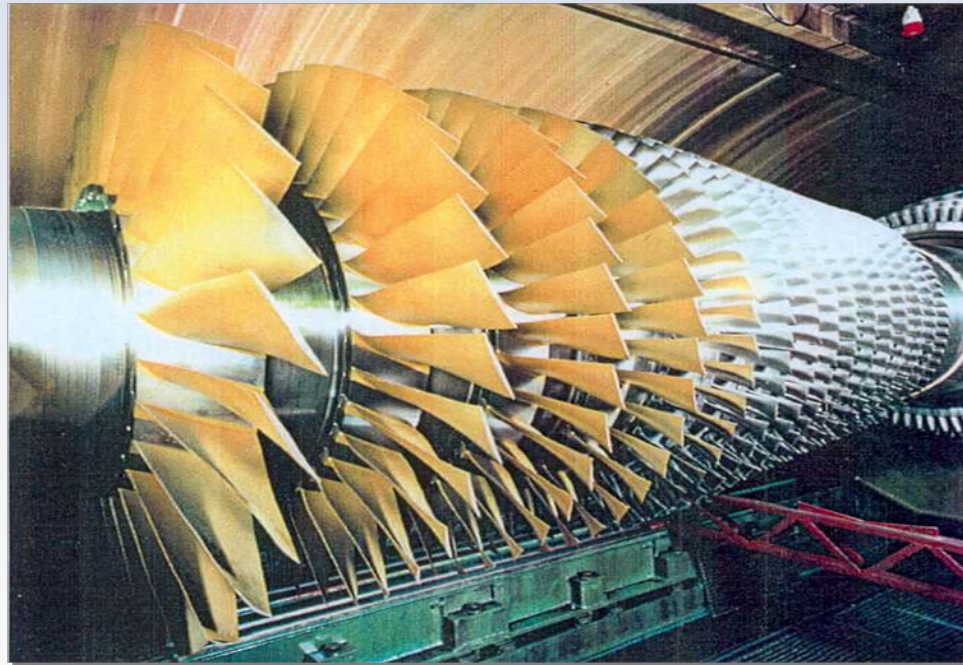
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DYNARDO GmbH
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- **Parametric Process Integration**
- **Sensitivity Analysis**
- **Design Optimization**
 - Evolutionary Algorithm
 - Adaptive Response Surface Method
- **Robustness Evaluation**
-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

Motivation



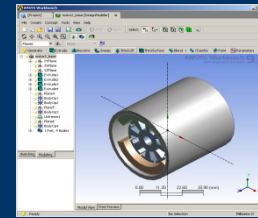
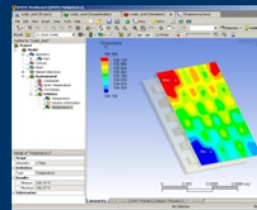
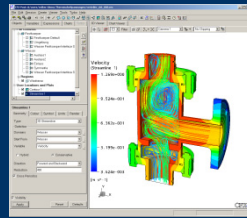
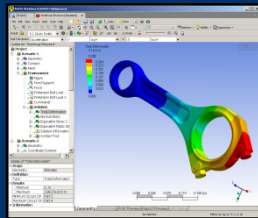
Power Plant	1000 MW
Efficiency	50 %
Increase of 1%	+20 MW
=Electricity for	120 000 Inhabitants

Workbench Platform & optiSLang



ANSYS Workbench

Structural Mechanics - Fluid Dynamics - Heat Transfer - Electromagnetic



A Multi-Physics Design and Analysis System



Sensitivity

Optimization

Robustness

Reliability

Robust Design

optiSLang

The background features a central globe with the ANSYS logo overlaid. The globe is surrounded by a complex network of glowing blue and orange lines, resembling a magnetic field or data flow. The text is positioned to the right of the globe.

**Parameterization
Process & Geometry**

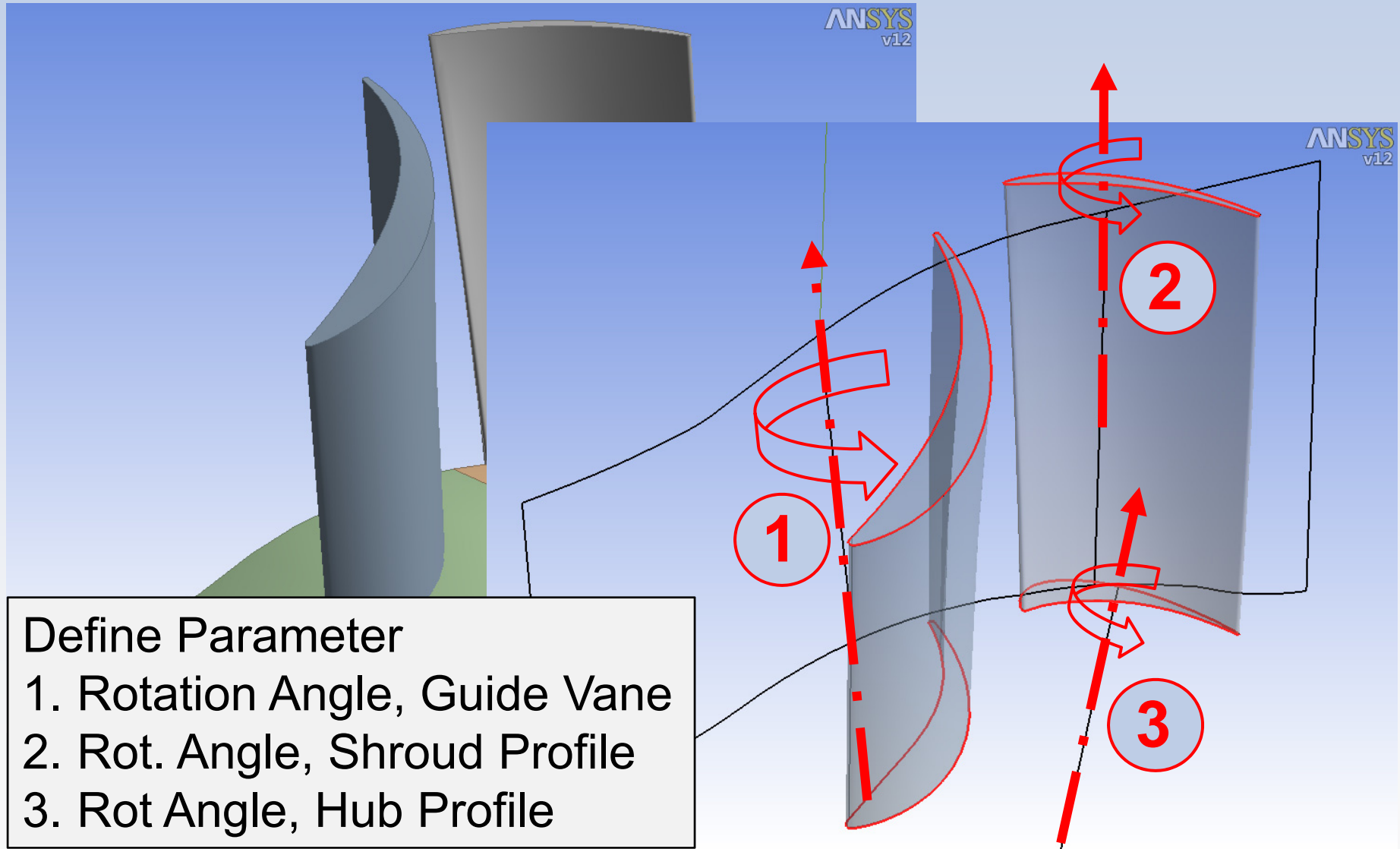
Sensitivity Analysis

Design Optimization

Robustness Evaluation

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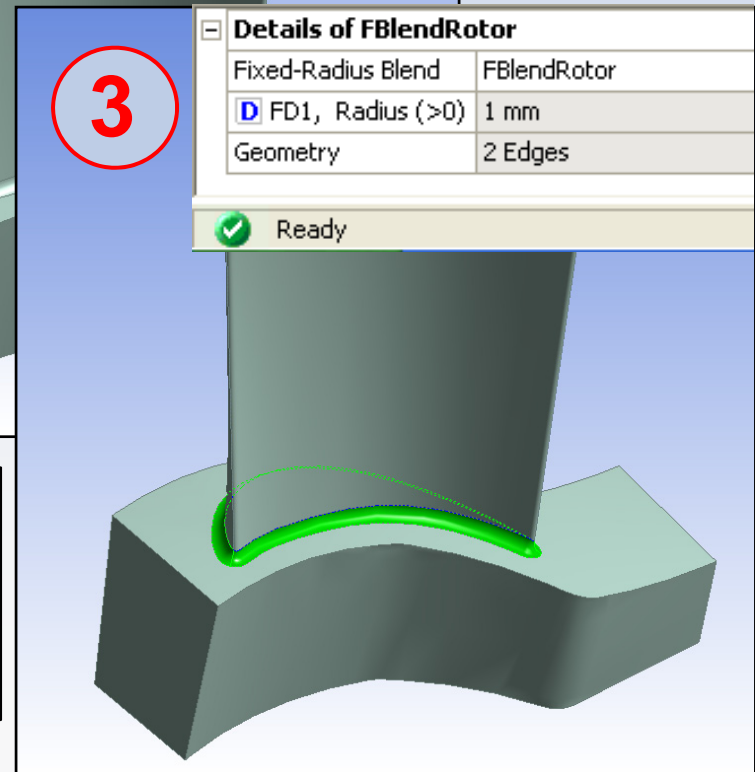
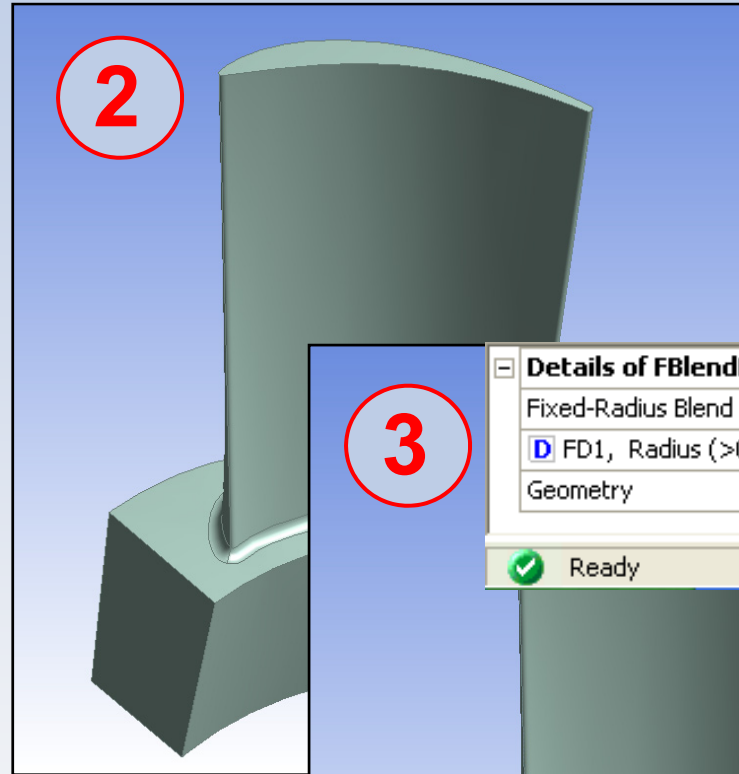
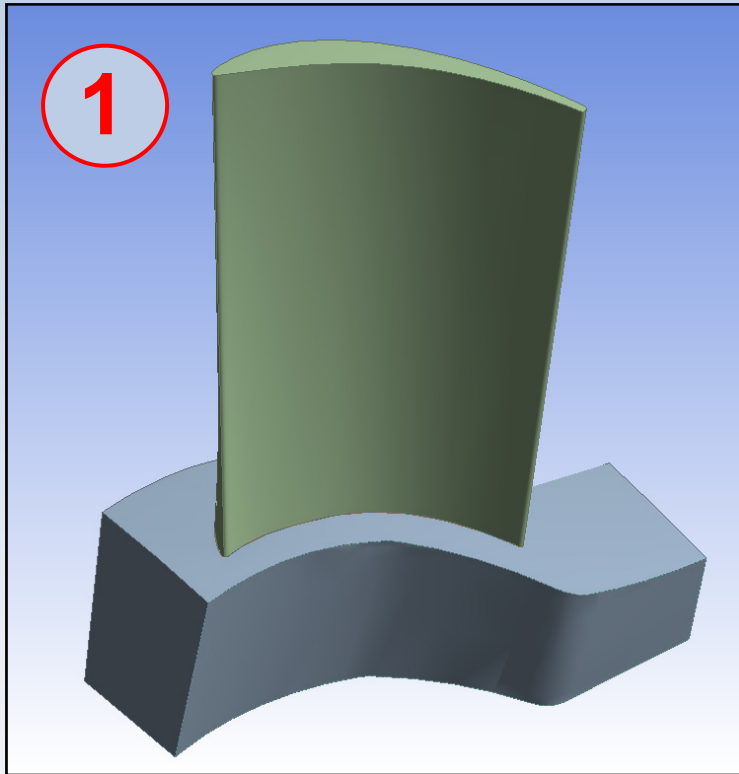
Parameterization of the Geometry



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

ID	Parameter Name	Value	Unit
P5	myomega	-2094.4	radian s ⁻¹
P15	DS_hub_angle	0	
P16	DS_shroud_angle	0	
P17	DS_gv_angle	0	
P20	Ttin	1000	K
P21	ptin	3E+05	Pa
P22	pout	87000	Pa
P23	myAirCP	1004.4	J kg ⁻¹ K ⁻¹
P24	myAirR	287.1	J kg ⁻¹ K ⁻¹
P25	mySteelCP	434	J kg ⁻¹ K ⁻¹
P26	mySteelDensity	7850	kg m ⁻³
P27	mySteelLambda	60.5	W m ⁻¹ K ⁻¹
P28	DS_FBlendRotor	1	
P30	Young's Modulus	2E+11	Pa
P31	Poisson's Ratio	0.3	
P7	Tratio	1.1158	
P8	myTorque	-576.75	J
P9	myeta	0.71645	
P10	ptratio	1.6738	
P11	myPower	1.2079E+06	W
P12	Temperature Maximum	688.26	C
P13	Total Deformation Maximum	0.00063589	m
P14	Equivalent Stress Maximum	2.2466E+09	Pa
P29	Density	7850	kg m ⁻³
P32	Thermal Conductivity	60.5	W m ⁻¹ C ⁻¹
P33	myMassFlow	11.566	kg s ⁻¹
P34	Equivalent Stress Blend Maximum	2.2466E+09	Pa
P35	Rotational Velocity Z Component	-2094.4	radian s ⁻¹

List of Design Points

Name	P5 - myomega	P15 - DS_hub_angle	P16 - DS_shroud_angle	P17 - DS_gv_angle	P20 - Ttin	P21 - ptin	P22
Current	-2094.4	0	0	0	1000	3E+05	87000

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

Property	Value
General	
Description	
Error Message	
Expression	P5
Usage	Derived
Quantity Name	Angular Velocity

Input Parameter = 15
Output Parameter = 9

Workbench Interface to optiSLang



The screenshot displays the ANSYS Workbench interface for a project named "AxialStageFSIblend". The Project Schematic shows a multi-physics model with three main analysis systems: A (Geometry), B (TurboGrid), and C (CFX). System A includes two Geometry objects and Parameters. System B includes TurboGrid and Turbo Mesh. System C includes CFX, Setup, Solution, Results, and Parameters. The CFX system is connected to two other analysis systems: "Steady-State Thermal (ANSYS)" and "Static Structural (ANSYS)".

The "optiPlug WB 12" dialog box is open in the foreground, allowing configuration of the optimization project. It includes the following fields and options:

- Write optimization project: [Dropdown]
- Optimization problem: [Dropdown]
- Lower bounds (-): 10 % Upper bounds (+): 20 %
- Update mode: Don't write files, show a warning message [Dropdown]
- Save results
- Show WB GUI during calculations

Red arrows highlight the "optiPlug..." label in the Project Schematic and the "optiPlug WB 12" dialog box, indicating the connection between the two.

Workbench Interface to optiSLang



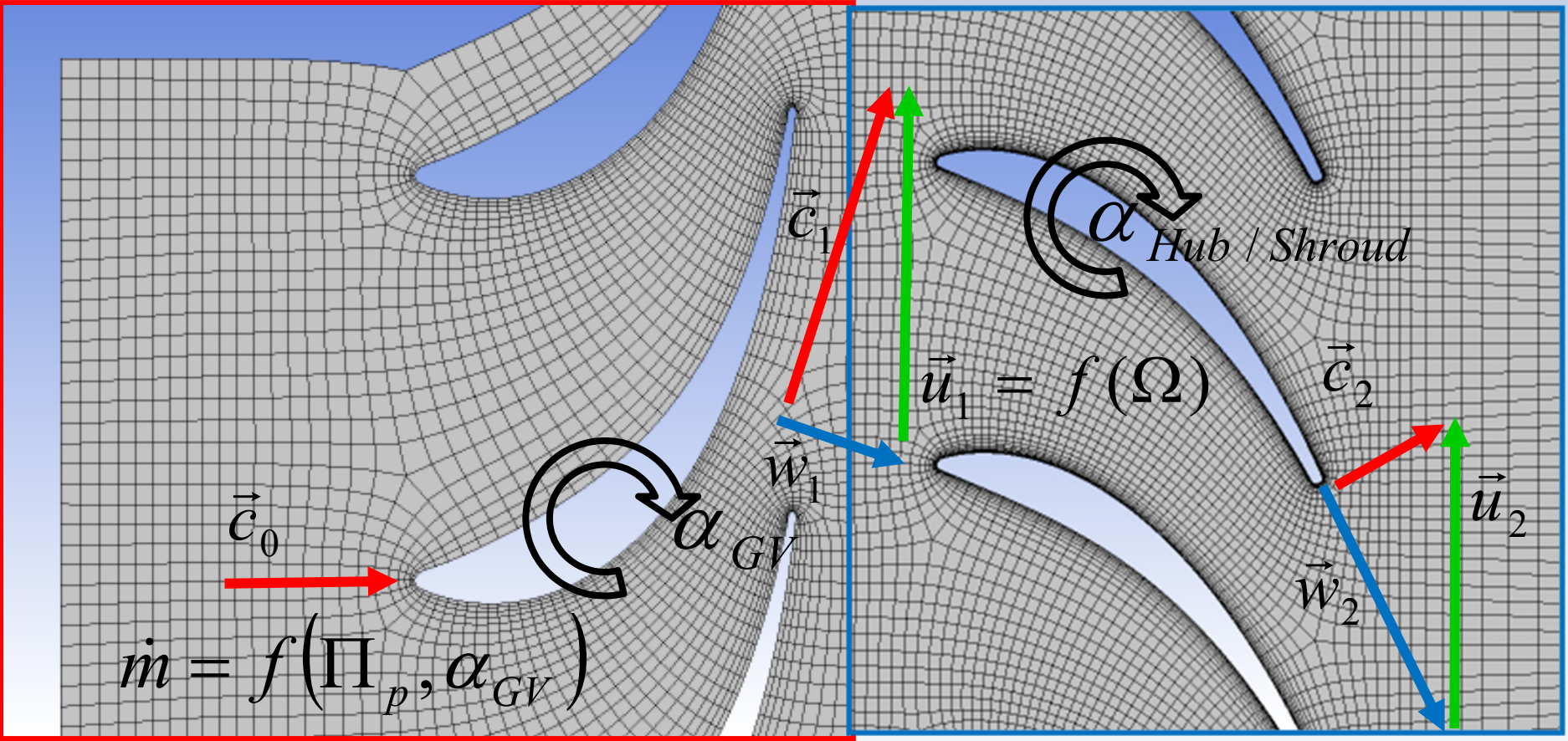
The screenshot displays the ANSYS Workbench interface for the optiSLang 3.0.1 workflow. The main window shows the 'Project manager' tab with a tree view of workflow tasks, including 'Result_monitoring'. A red arrow points from the 'Result_monitoring' task in the tree to the 'flowGuide Project Manager' dialog box. The dialog box has an 'Import project' radio button selected. Another red arrow points from the 'Import project' option to a file selection dialog box. This dialog box shows the file 'AxialTurbineFSIblend.fgpr' selected in the 'workflows' folder. The 'flowGuide Project Manager' dialog also shows the 'Import Project' section with fields for 'Project name' and 'Project directory', and a file browser showing the selected project file.

Parameter Attributes



Input Parameter	Parameter Name	Initial Value	Type
Blade Angles	$\alpha_{GV}, \alpha_{Hub}, \alpha_{Shroud}$	$0^\circ, 0^\circ, 0^\circ$	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

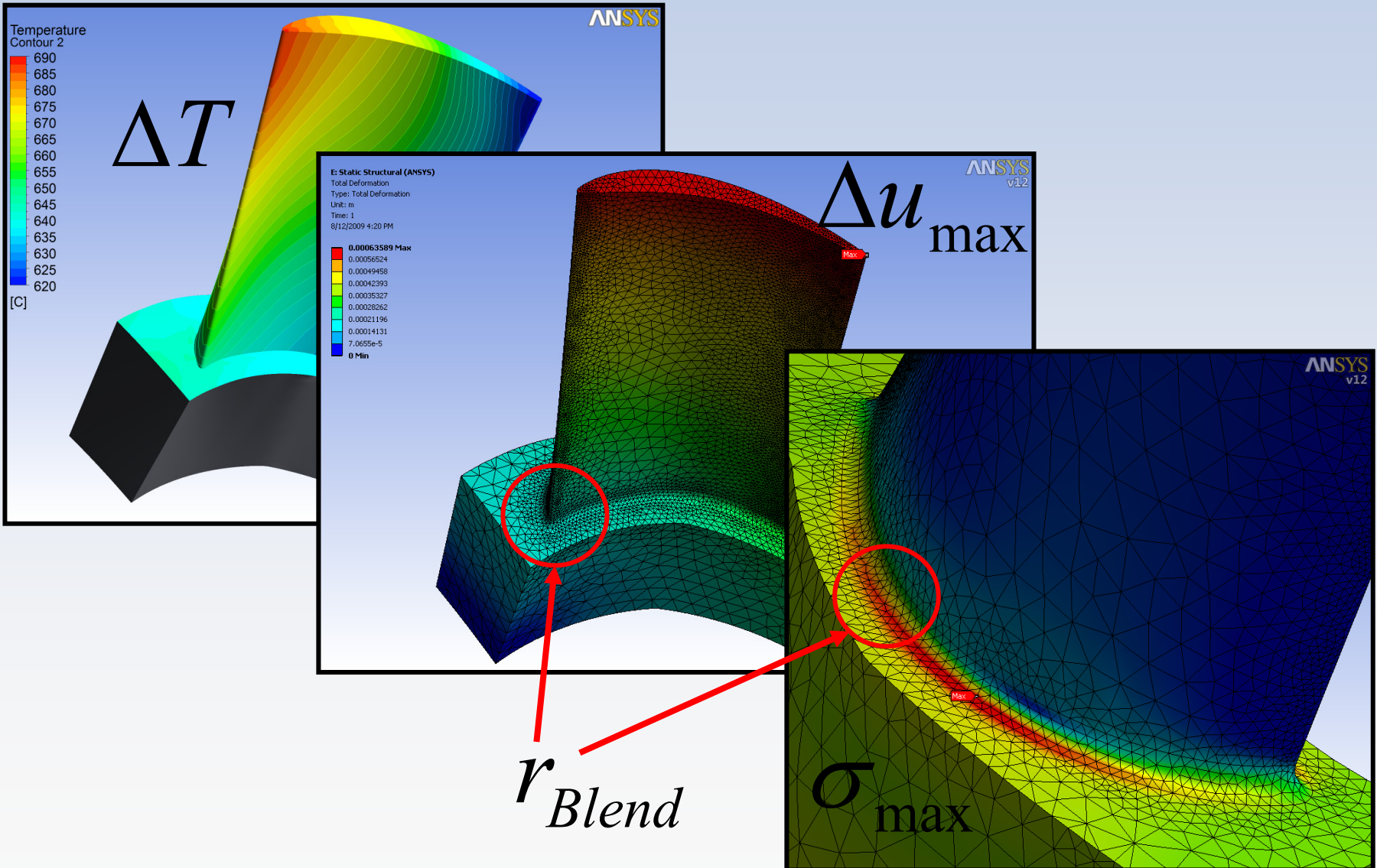
Parameter Physics, Fluid Flow



$$\eta = f(\Theta_T, \Pi_p)$$

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

Parameter Physics, Mechanics





**Parameterization
Process & Geometry**

Sensitivity Analysis

Design Optimization

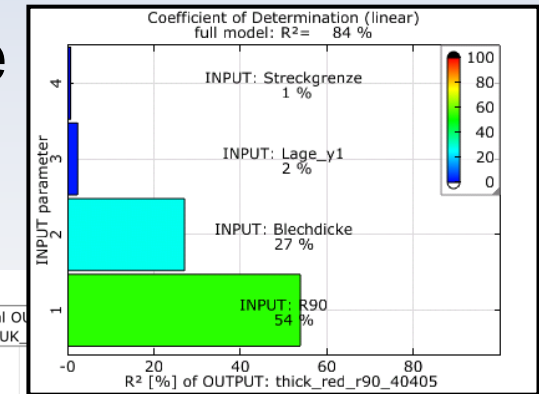
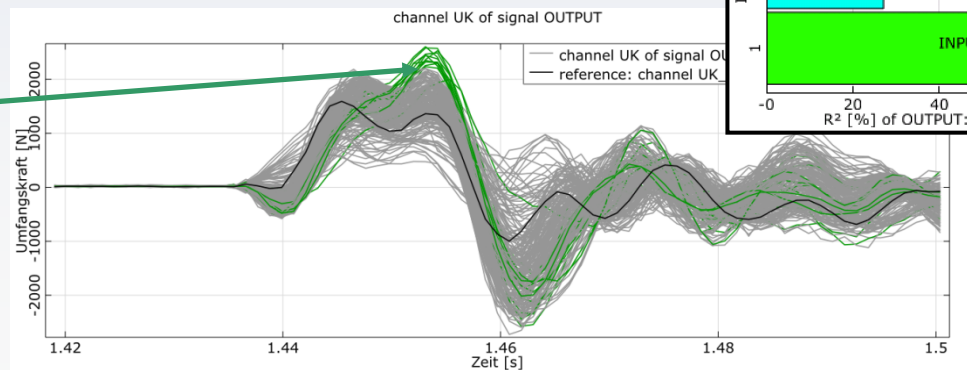
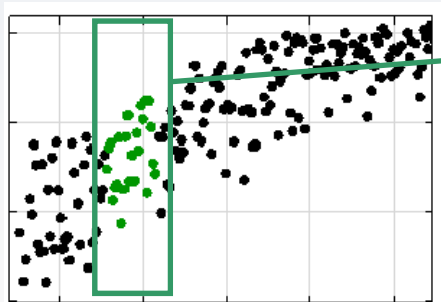
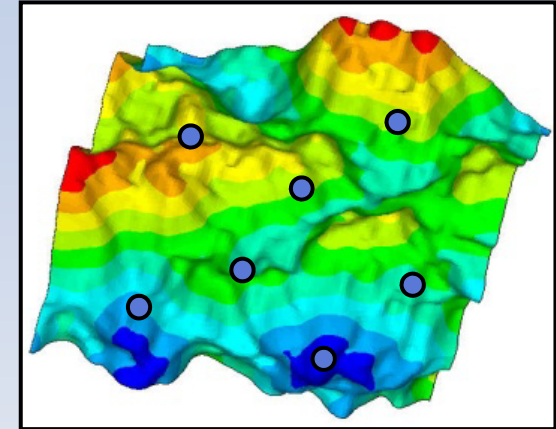
Robustness Evaluation

Sensitivity Analysis

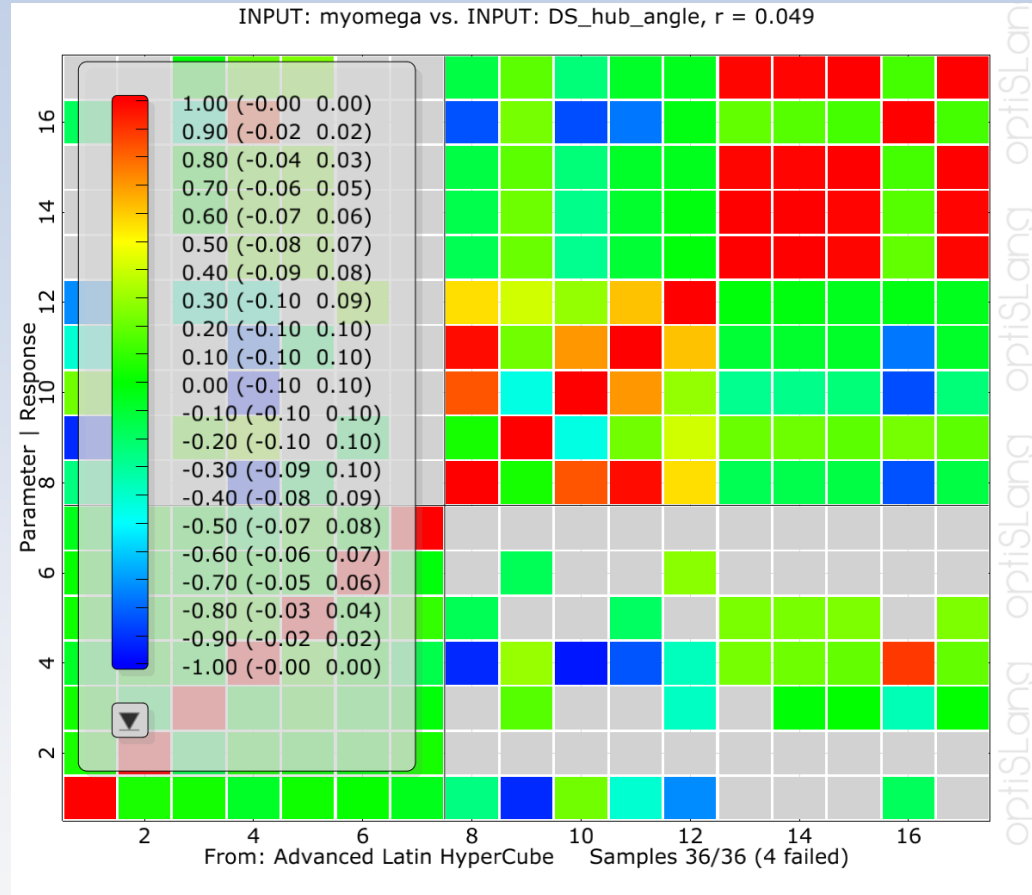
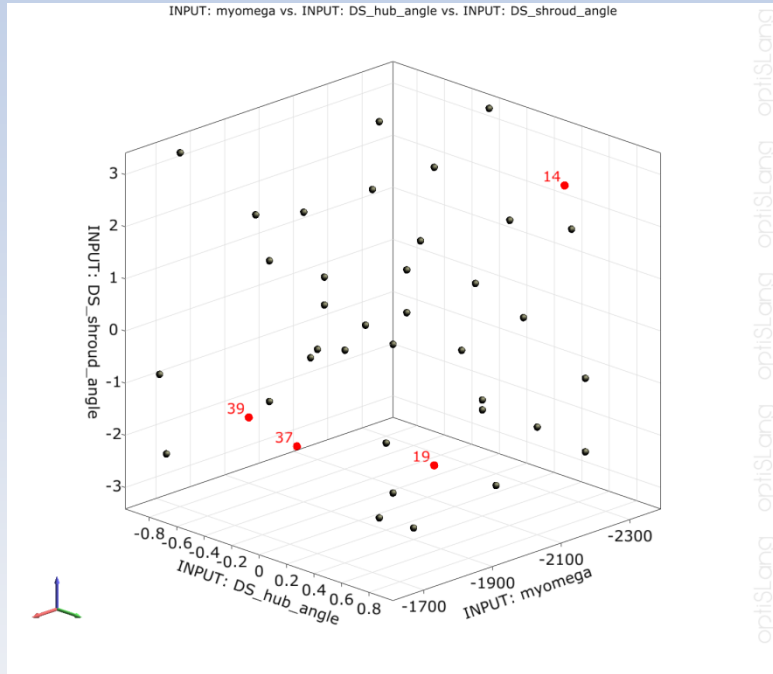
1. Scanning the Design Space with optimized LHS, variation and correlation are investigated

2. Identification of important variables

- Check Variation of Design Space
- Check Coefficient of Importance

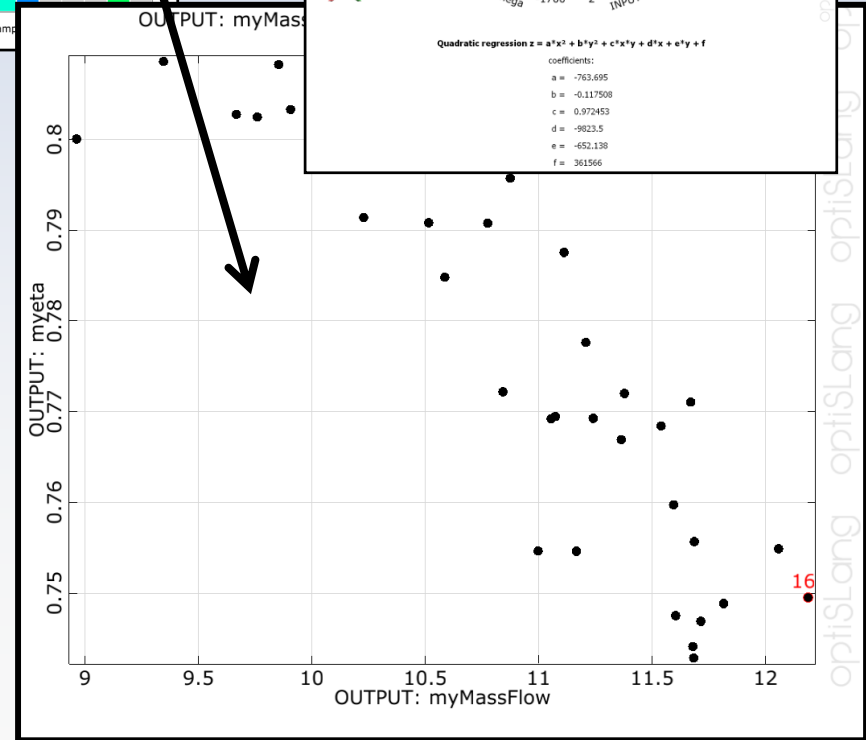
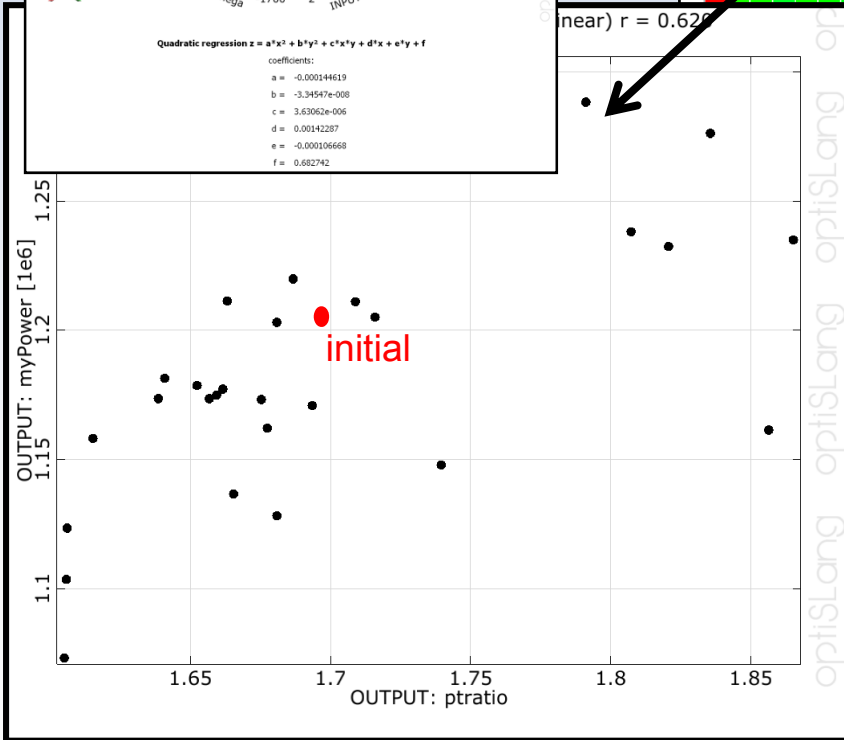
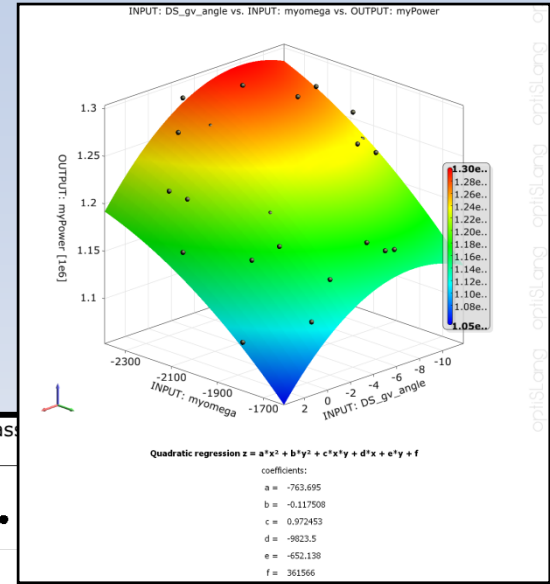
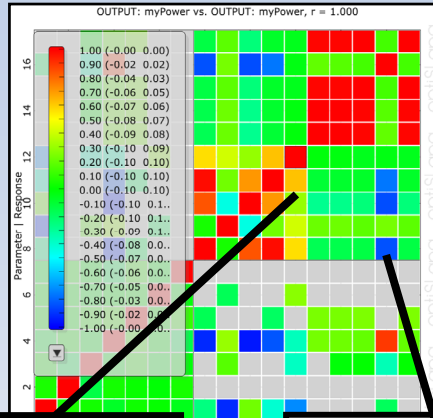
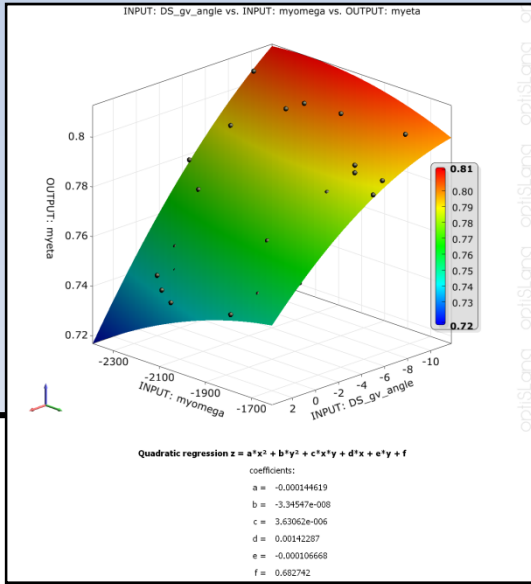


Latin Hypercube and Confidences



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

Variation of Design Space

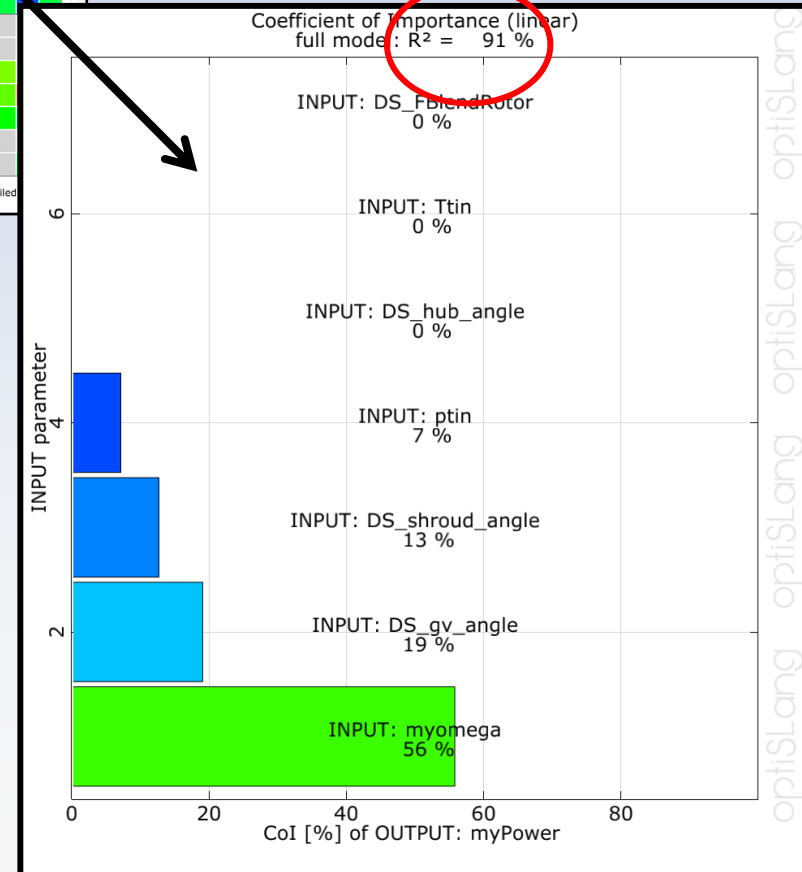
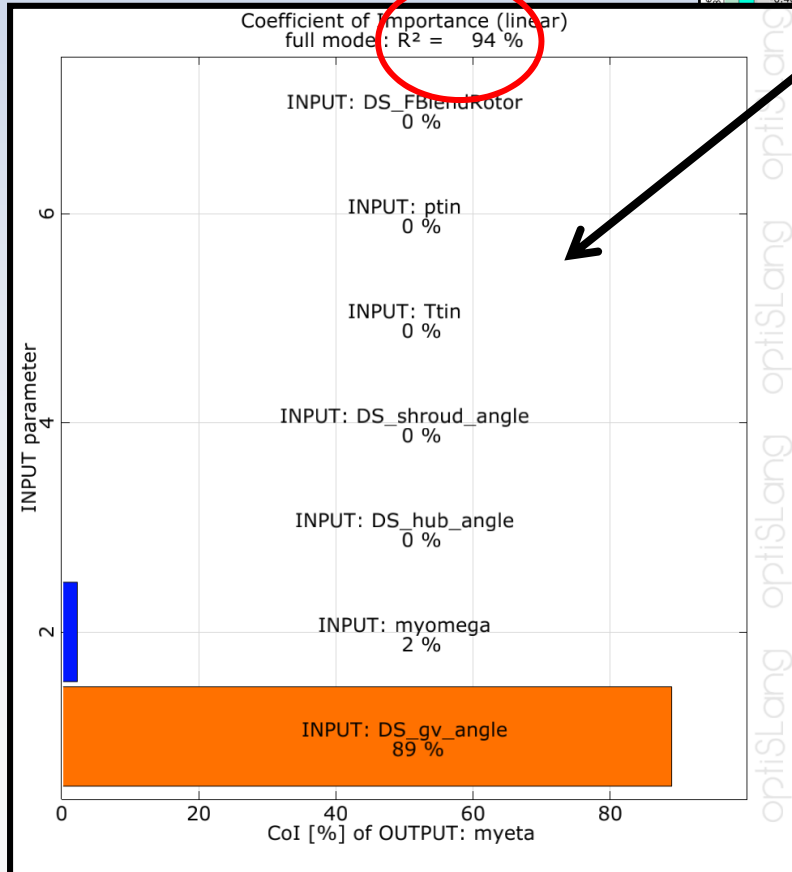
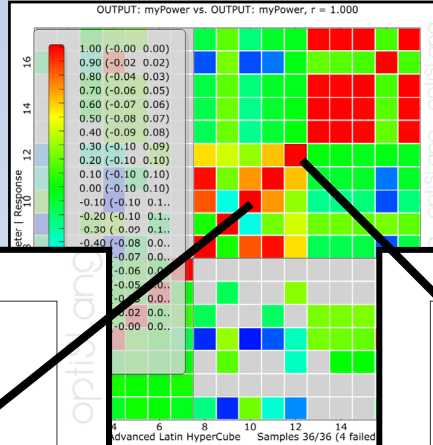


Coefficient of Importance, CoI

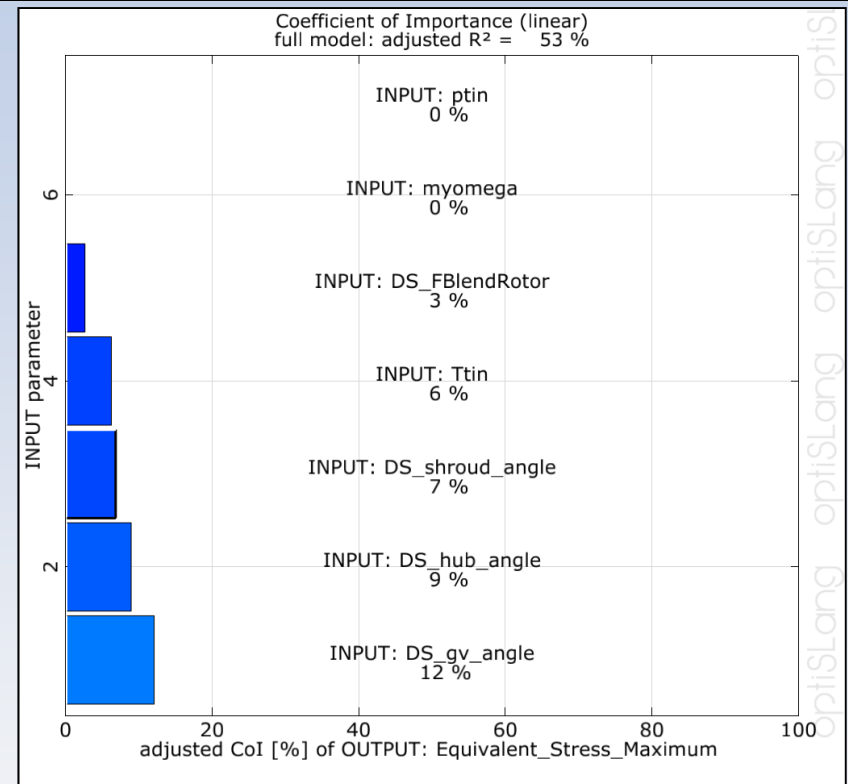
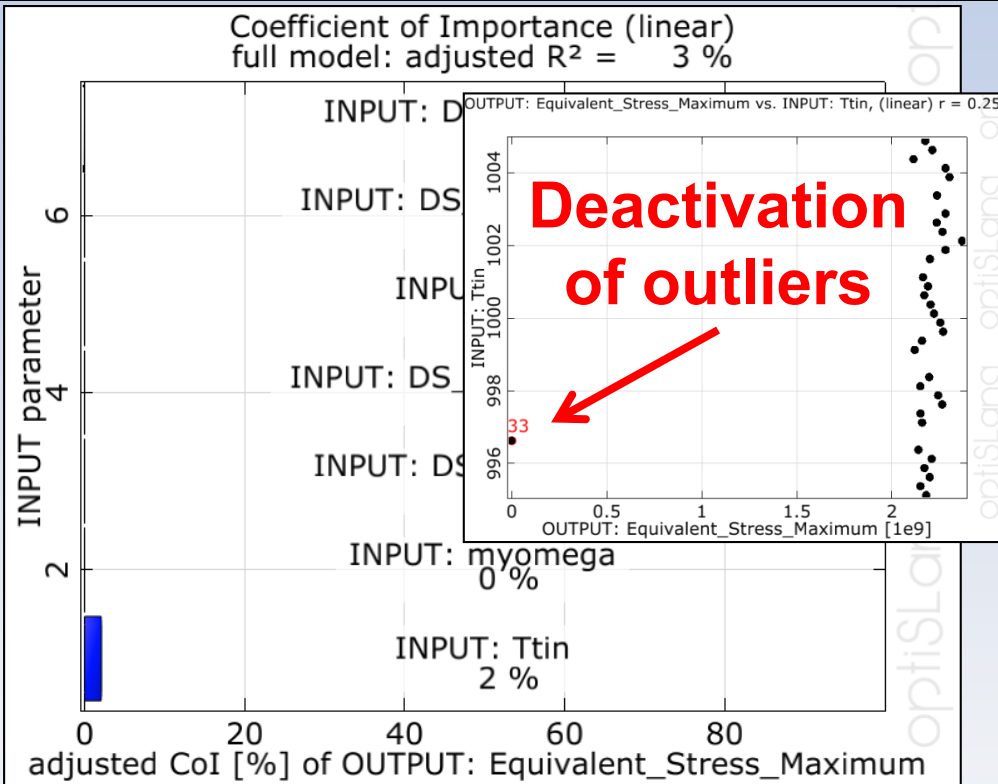


CoI=94% > 80%

CoI=91% > 80%



Coefficient of Importance, CoI

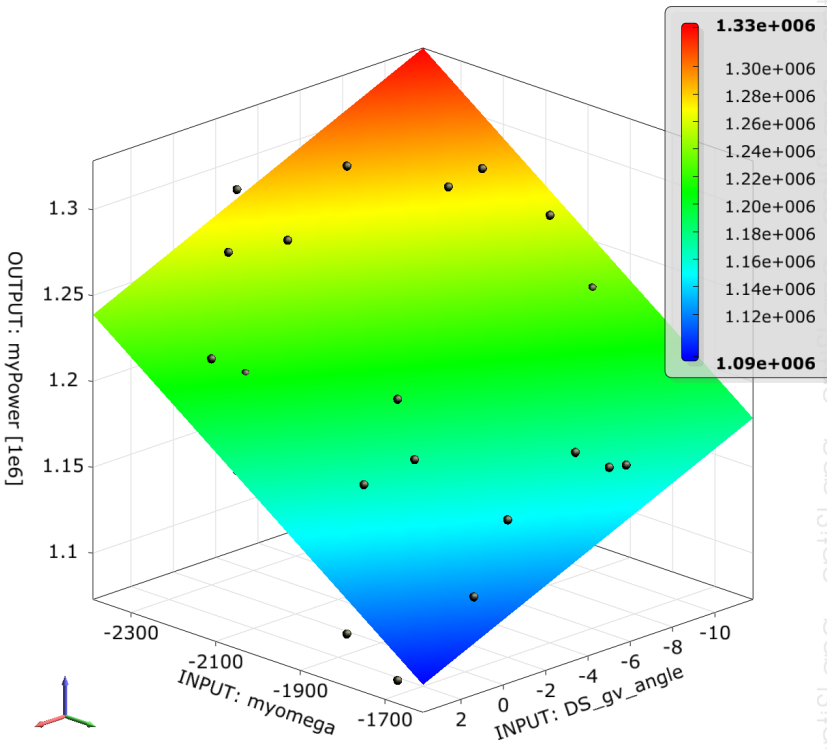


50% variance of the stress variation can be explained by the given n = 7 design variables

Meta-Model of Prognosis, MoP



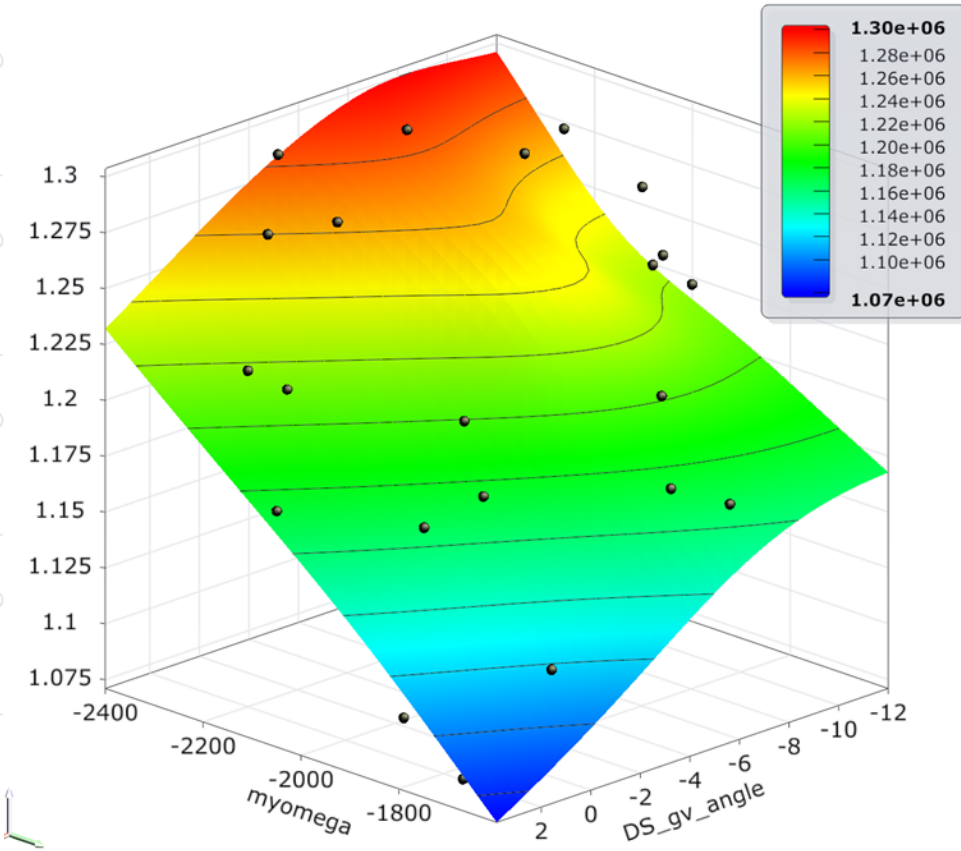
INPUT: DS_gv_angle vs. INPUT: myomega vs. OUTPUT: myPower



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

coefficients:
a = -5740.83
b = -191.993
c = 801806

MLS approximation of myPower
Coefficient of Prognosis = 96 %



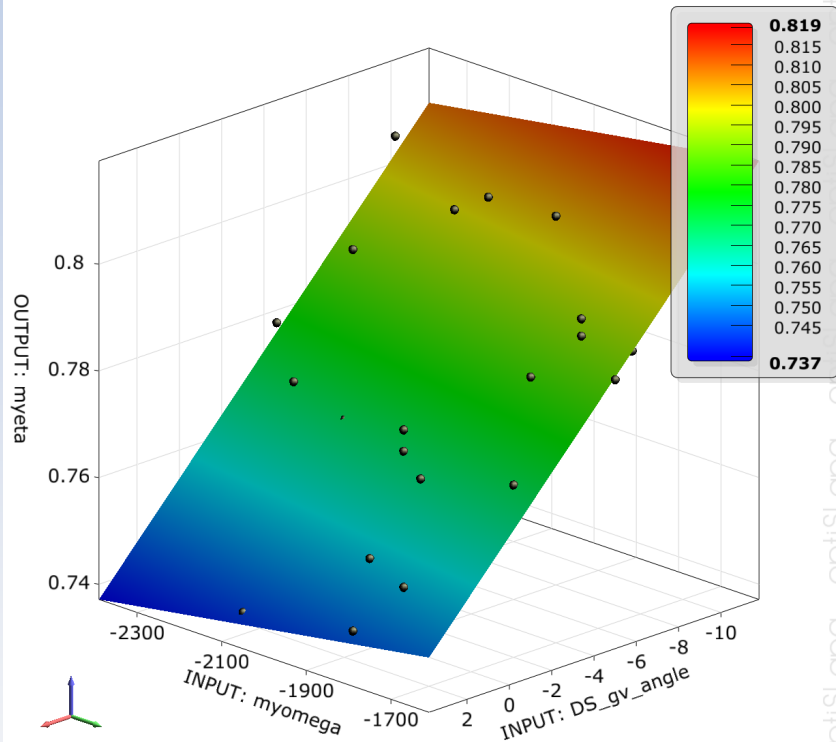
Response Surface Output: Power

Meta-Model Output: Power

Meta-Model of Prognosis, MoP



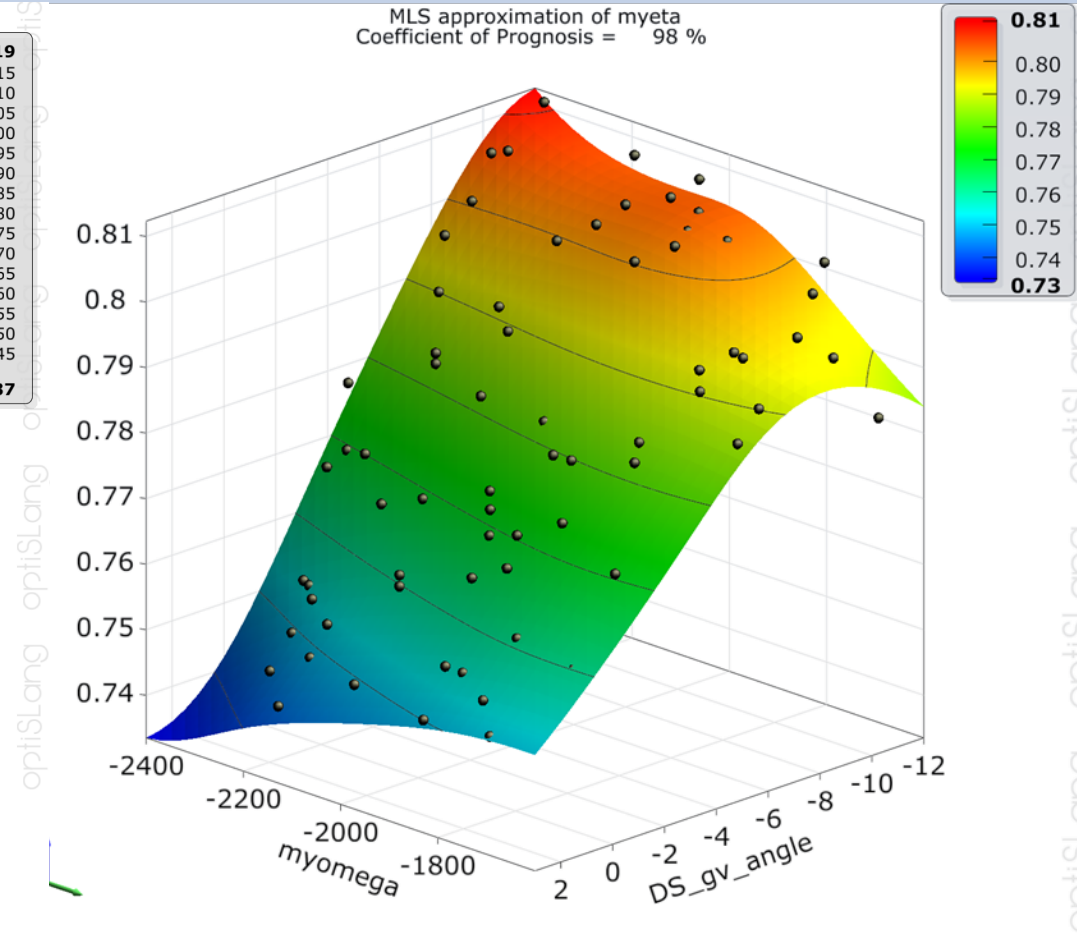
INPUT: DS_gv_angle vs. INPUT: myomega vs. OUTPUT: myeta



Linear regression $z = a*x + b*y + c$
coefficients:
a = -0.00461227
b = 1.31454e-005
c = 0.786101

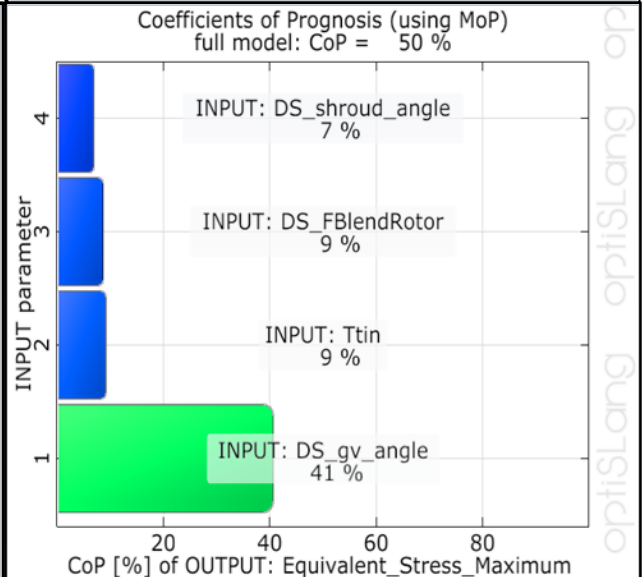
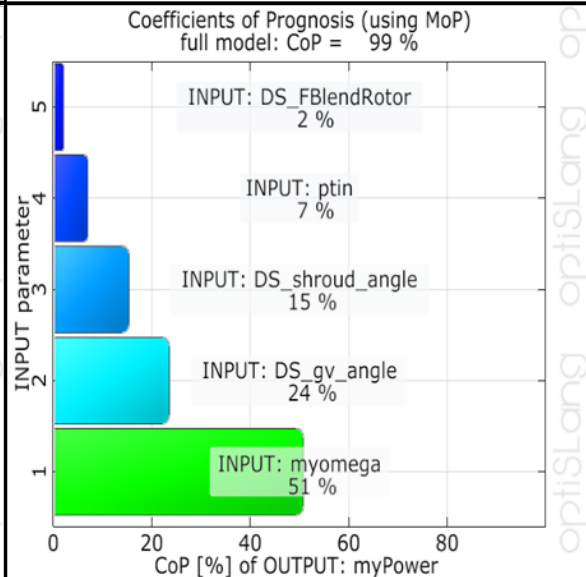
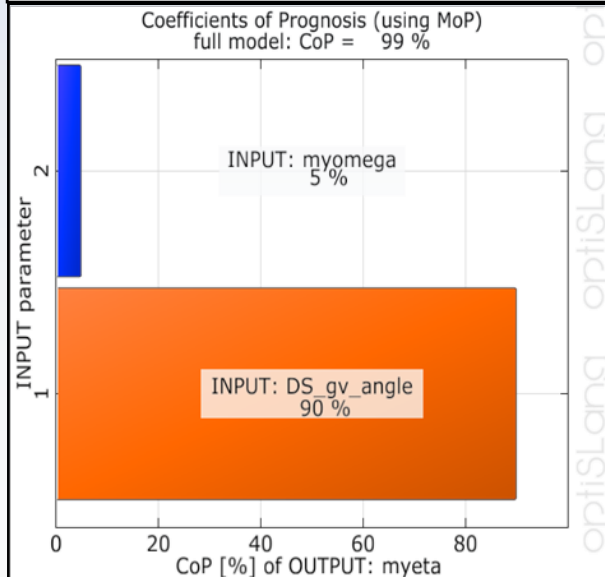
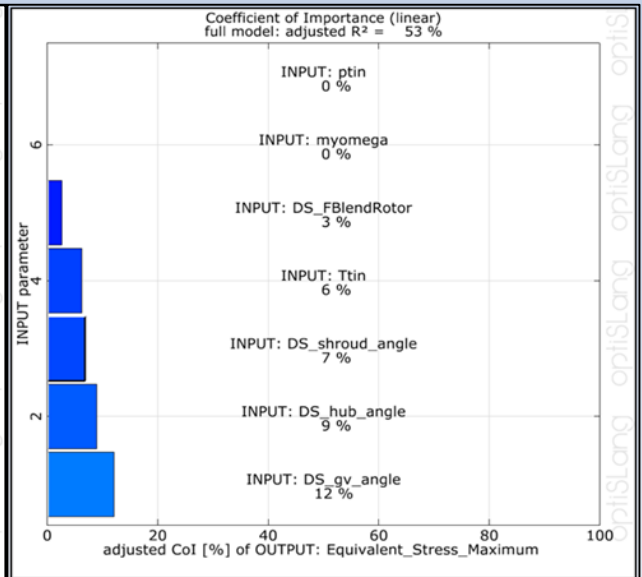
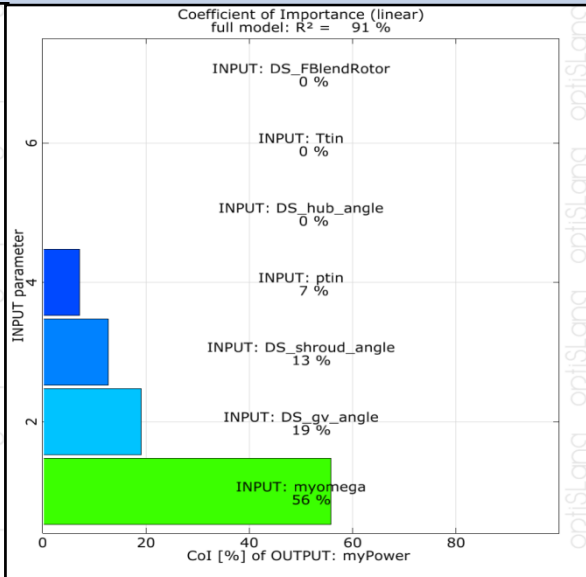
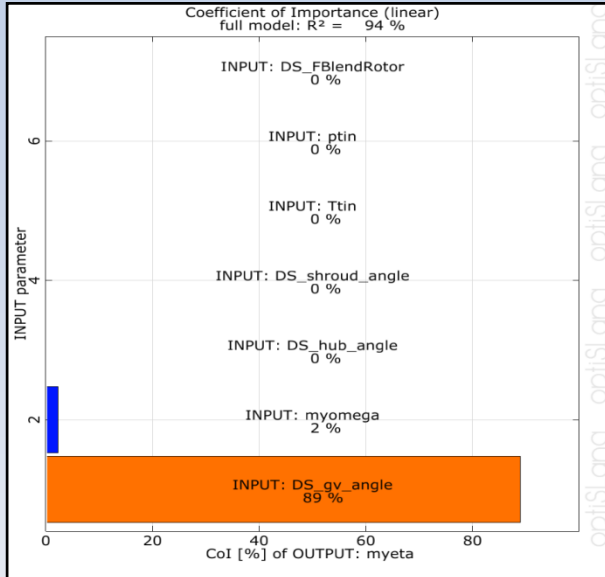
Response Surface Output: Efficiency

MLS approximation of myeta
Coefficient of Prognosis = 98 %

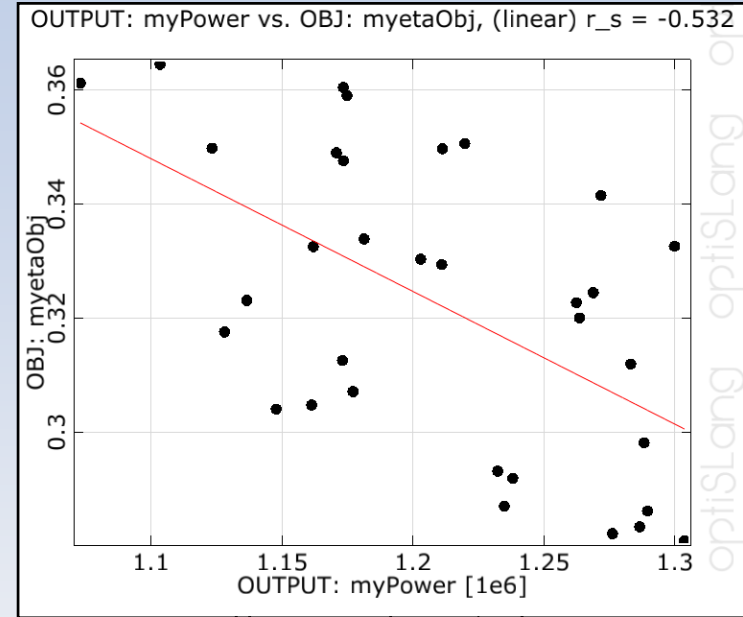
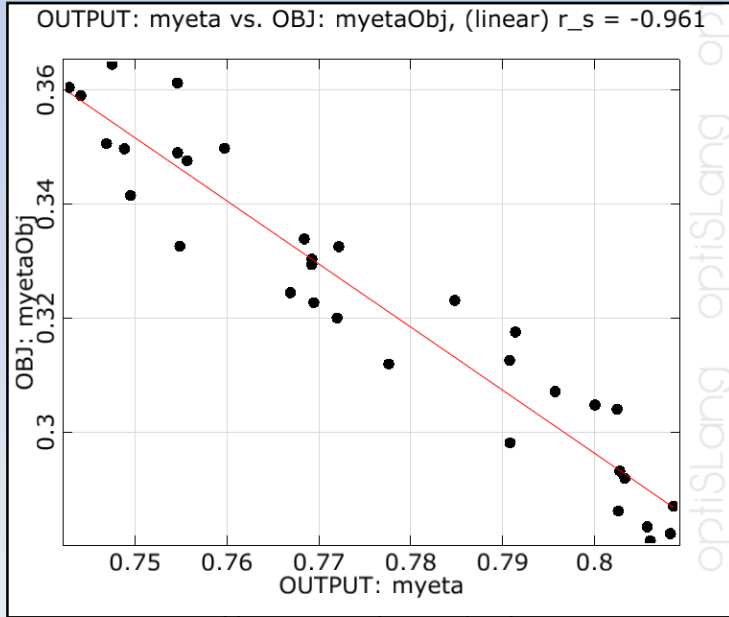


Meta-Model Output: Efficiency

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



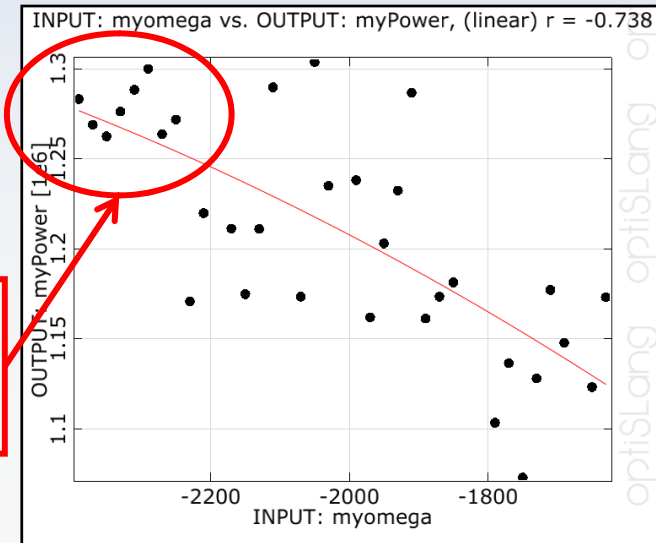
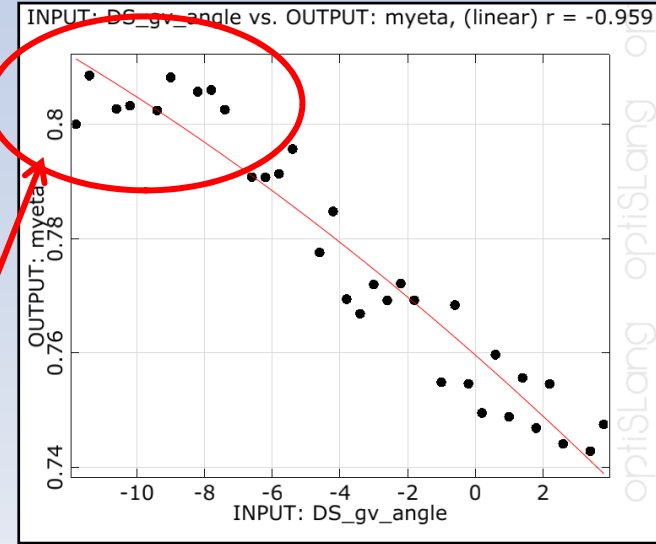
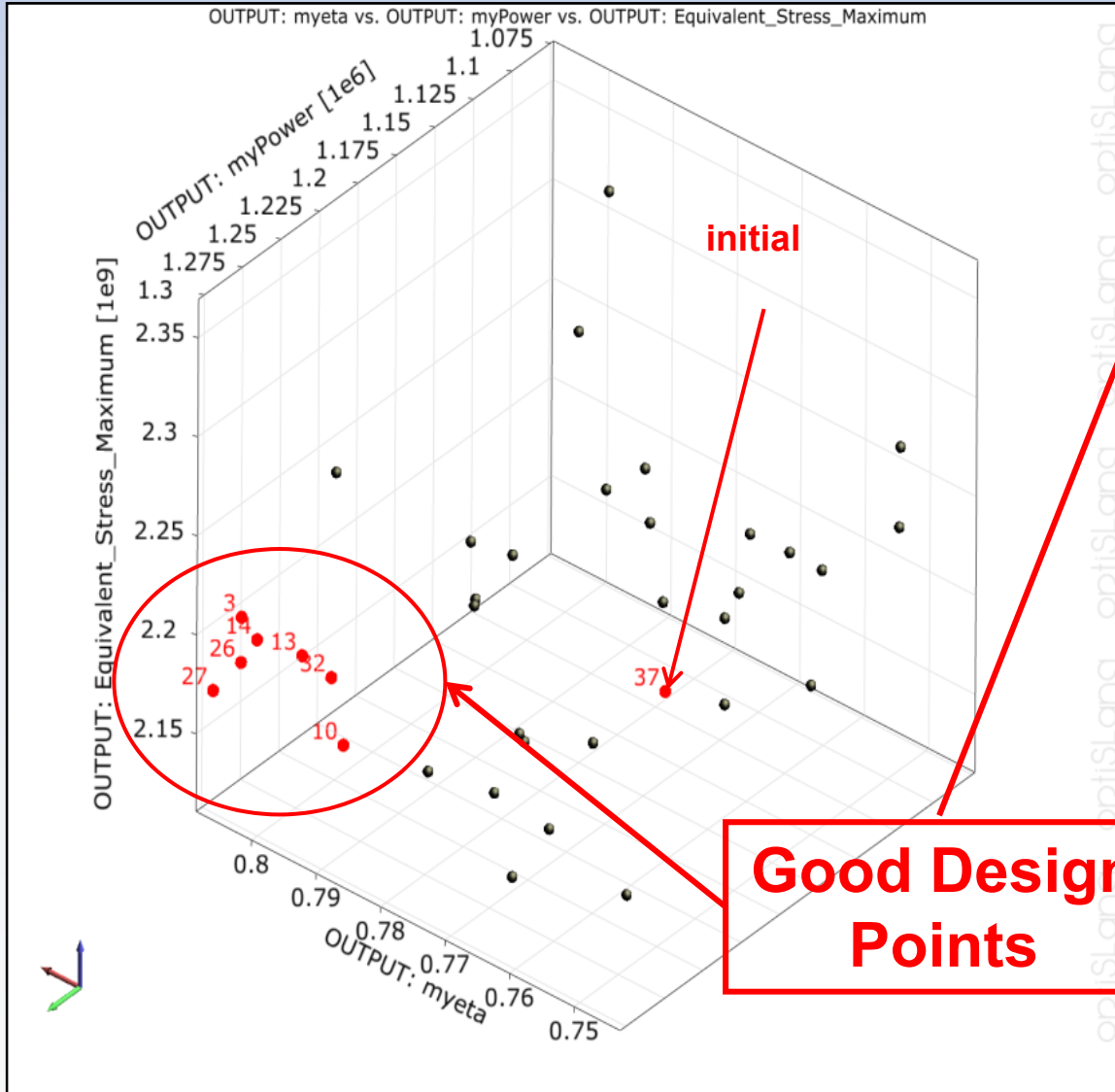
Objective Function



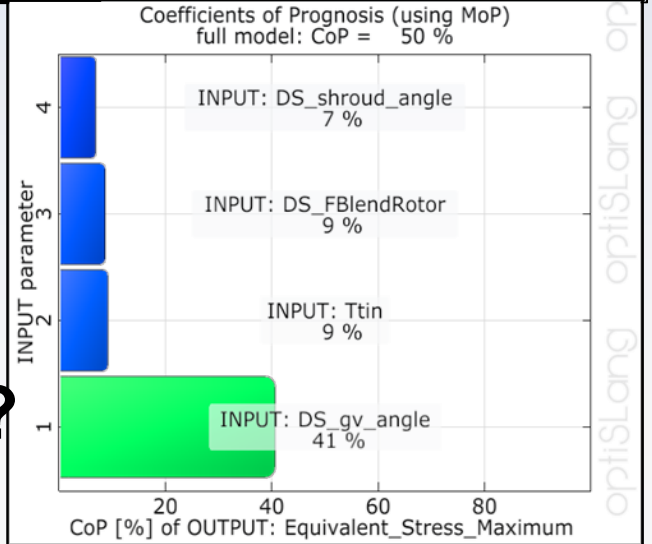
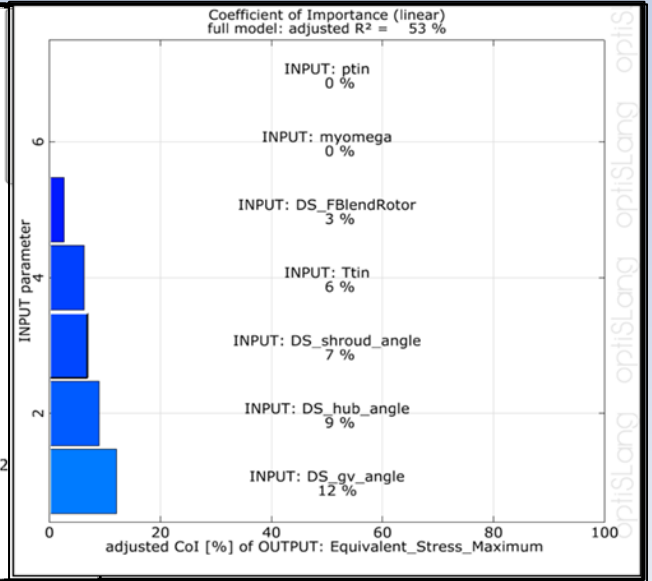
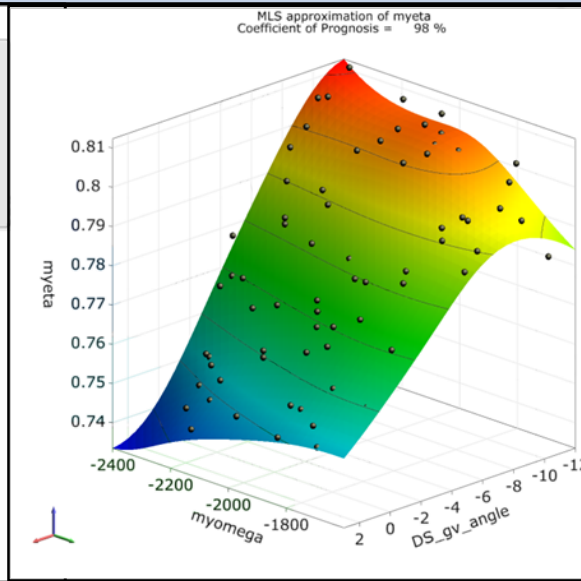
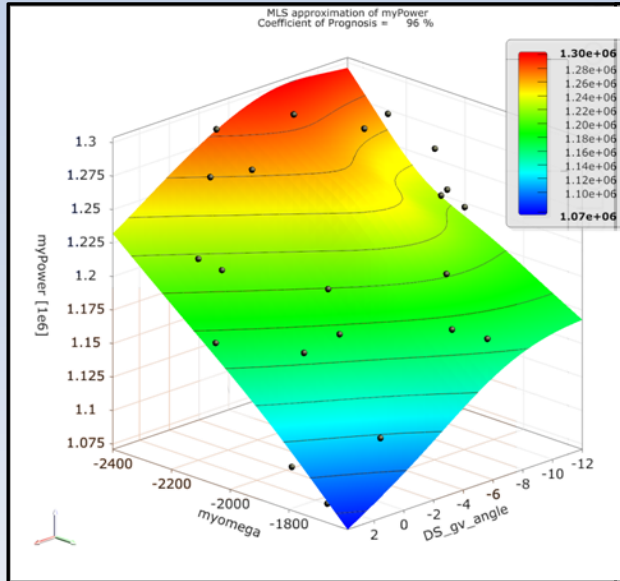
Target Function for Optimization:

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

Anthill Plots Objective



Conclusion Sensitivity Analysis



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

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**Parameterization
Process & Geometry**

Sensitivity Analysis

Design Optimization

Robustness Evaluation

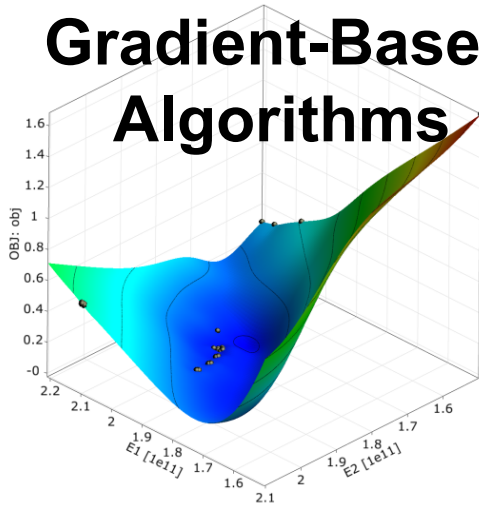
ANSYS®

Design Optimization



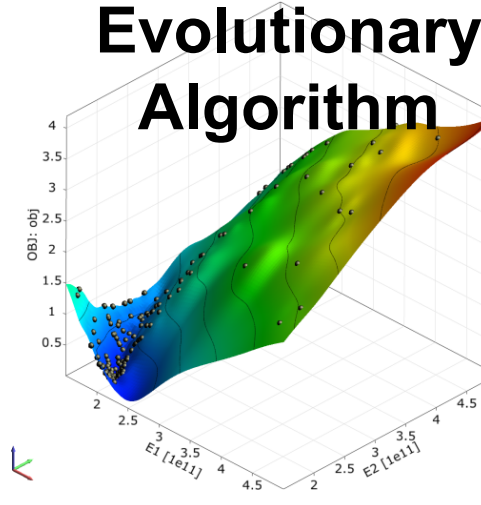
MLS approximation of OBJ: obj

Gradient-Based Algorithms



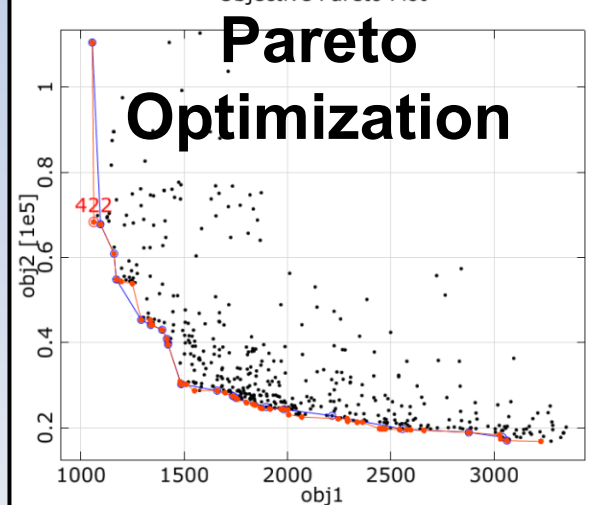
MLS approximation of OBJ: obj

Evolutionary Algorithm



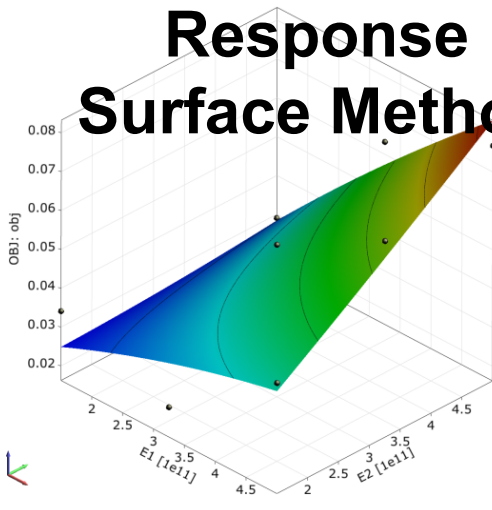
Objective Pareto Plot

Pareto Optimization



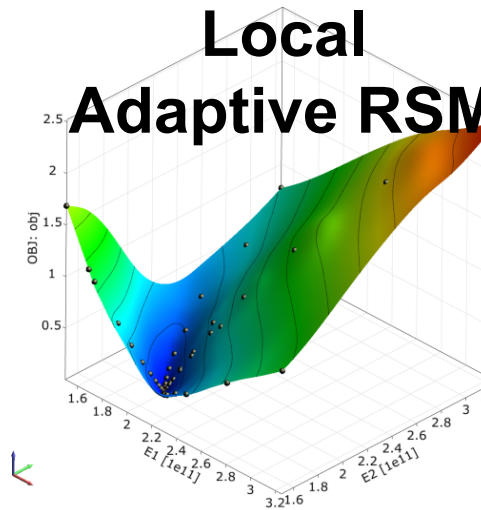
Quadratic regression of OBJ: obj

Response Surface Method



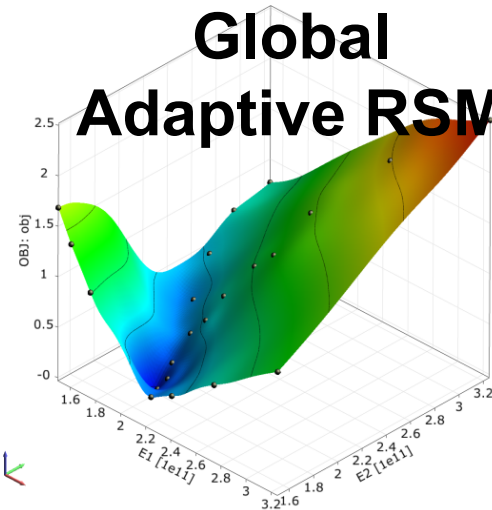
MLS approximation of OBJ: obj

Local Adaptive RSM



MLS approximation of OBJ: obj

Global Adaptive RSM



Optimization Strategy

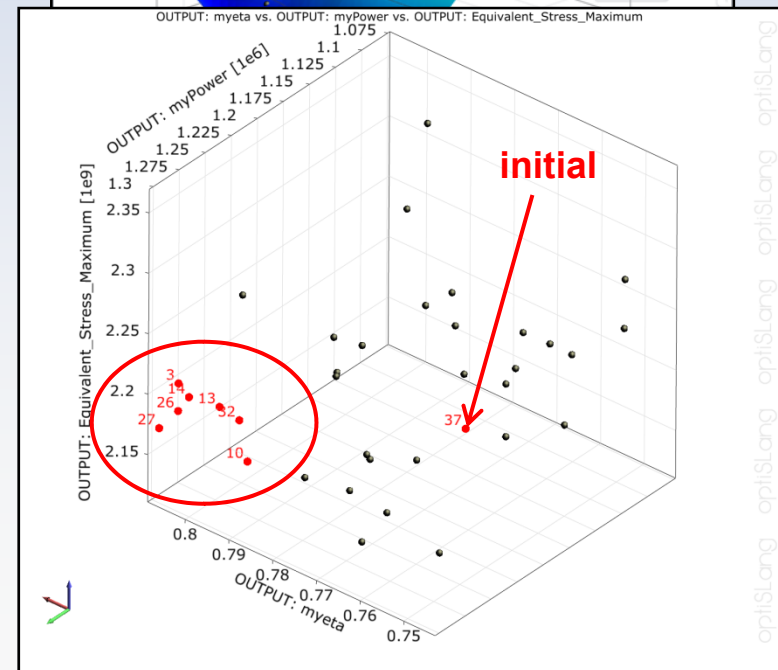
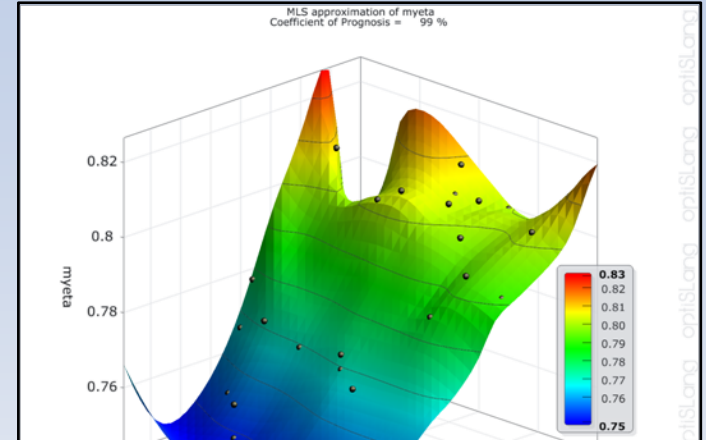


Sensitivity Analysis

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

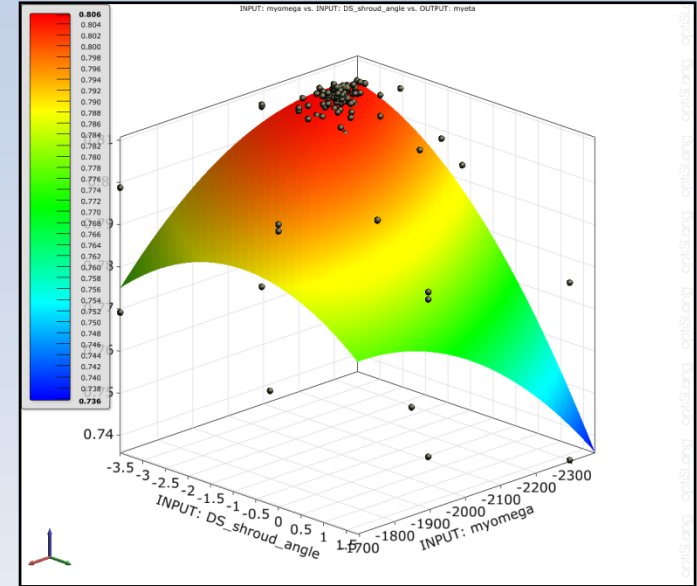
Strategy:

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



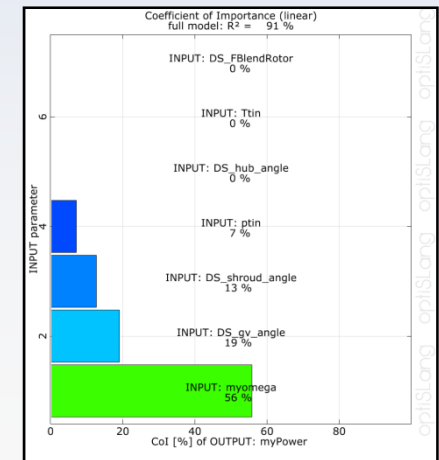
Sensitivity Analysis

- Shows Potential
- Indicates global optimum
- Parameter reduction



Strategy:

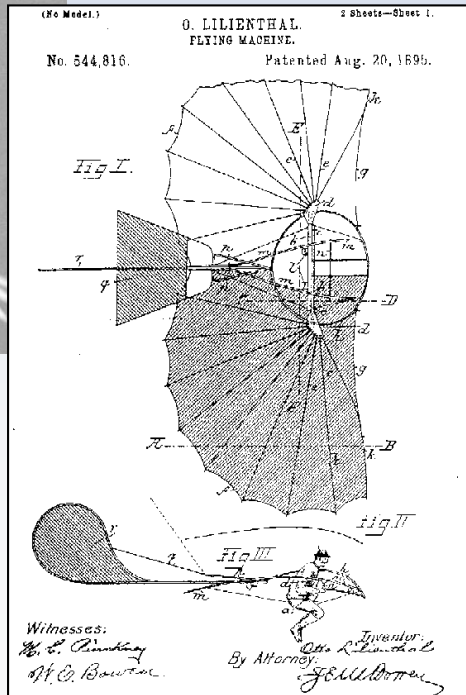
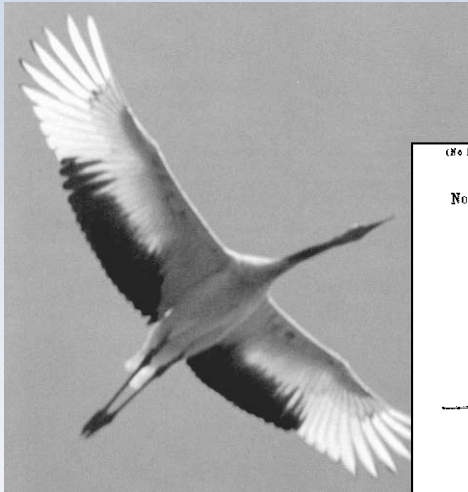
- Pre-optimization in sub space, ARSM
- Local improvement, EA (full space)
- Start design(s) from ARSM



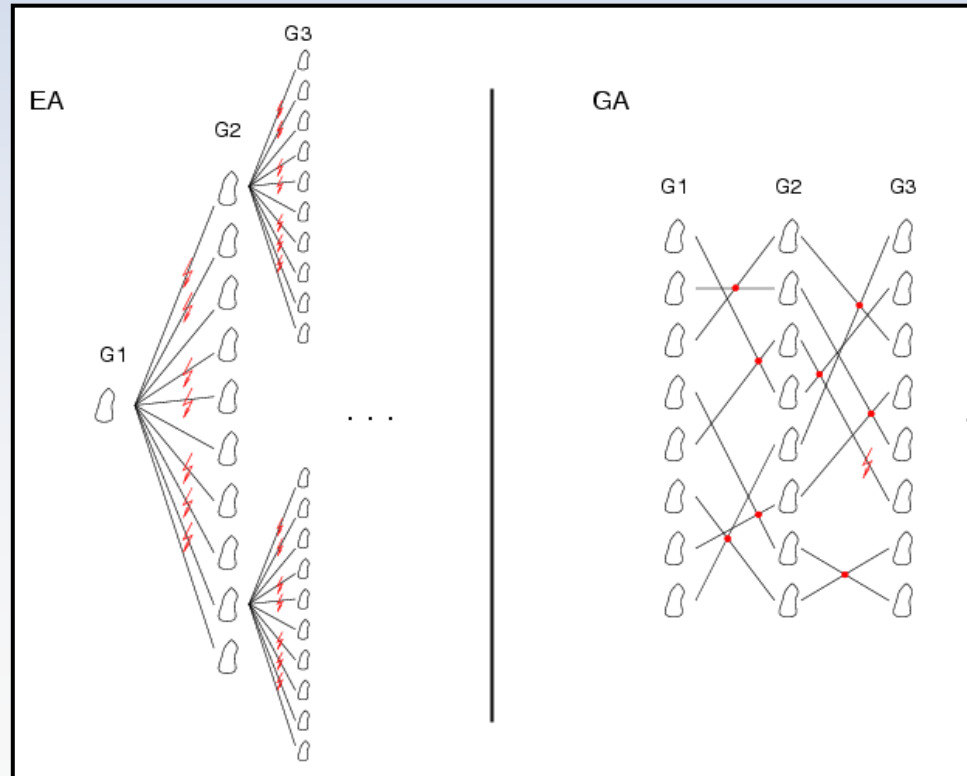
Evolutionary Algorithms (EA)

Optimization in Nature:

- Survival of the fittest
- Evolution due to mutation, recombination and selection



Evolution Algorithms [EA] Genetic Algorithms [GA]

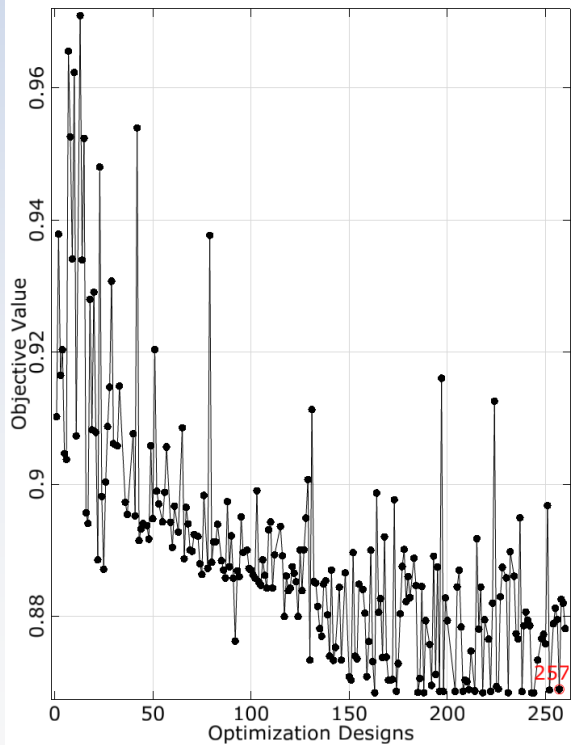


Evolutionary Algorithms (EA)

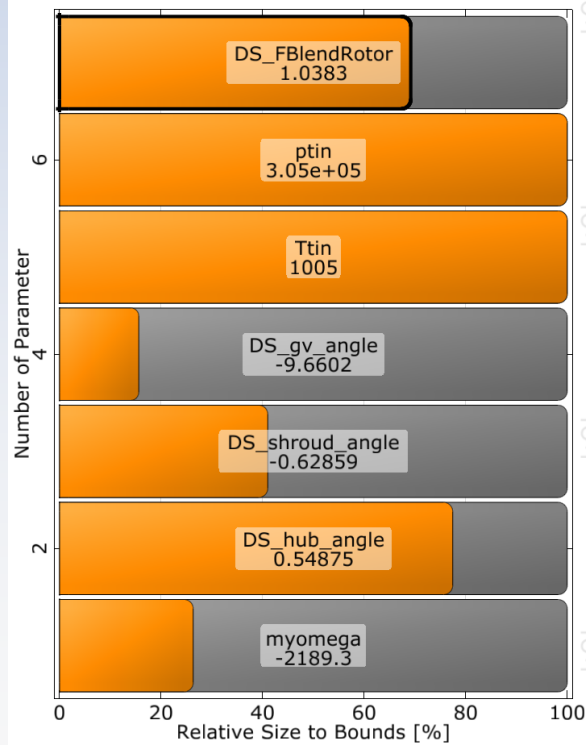


- History of the Evolutionary Algorithm

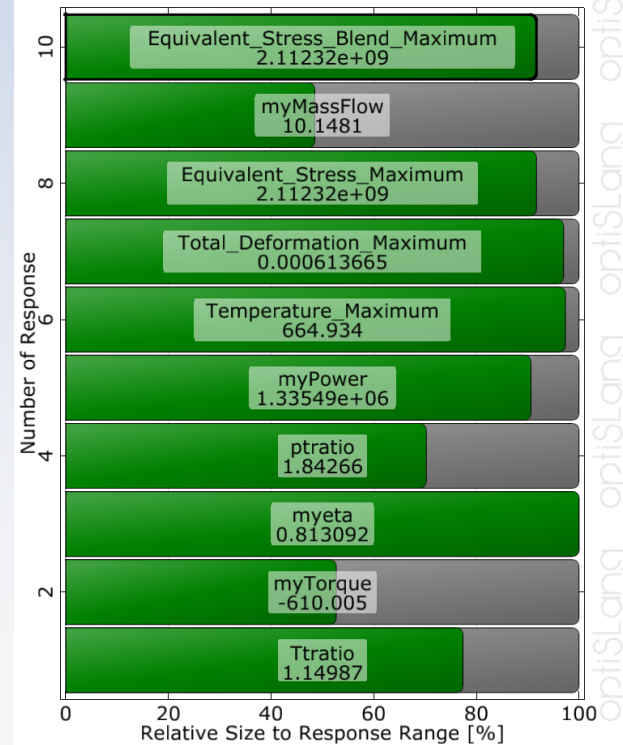
Objective History



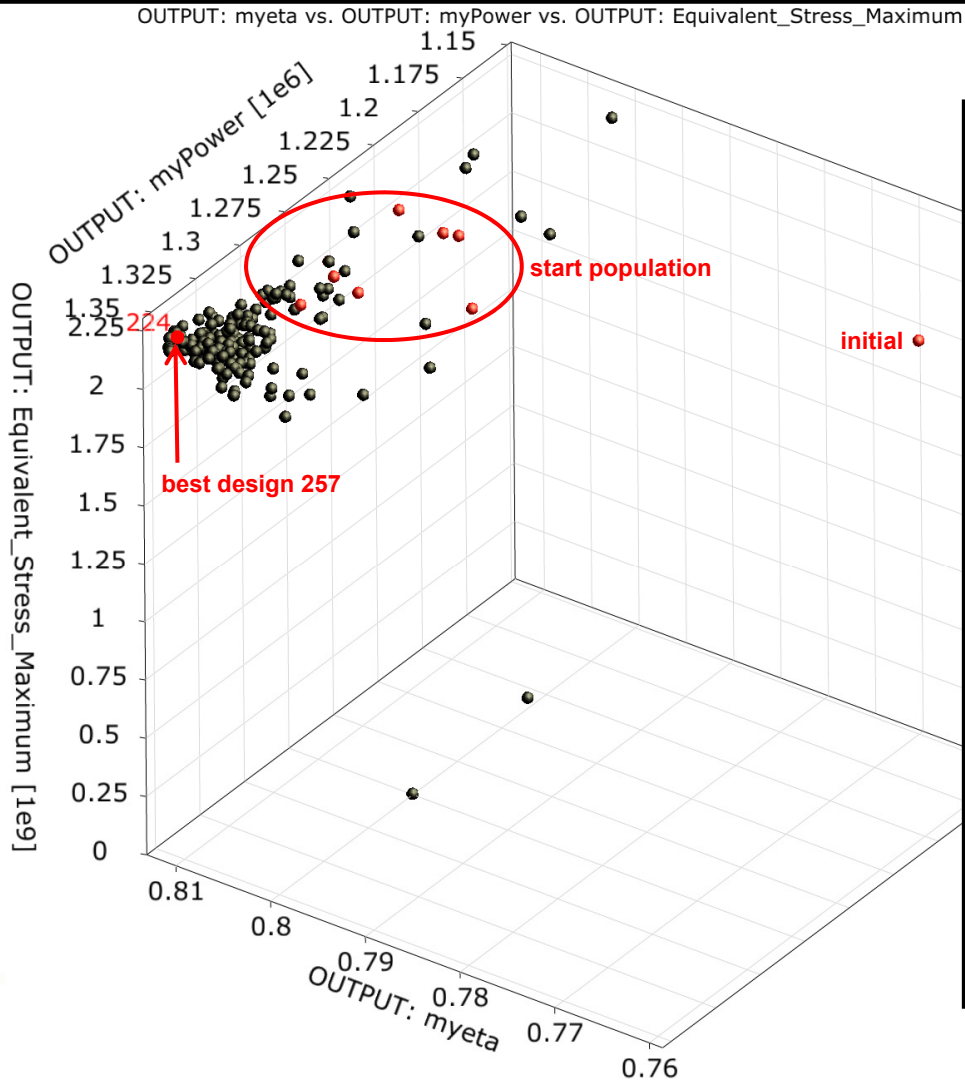
Design Number: 257



RESPONSE DATA: (Design Number: 257)

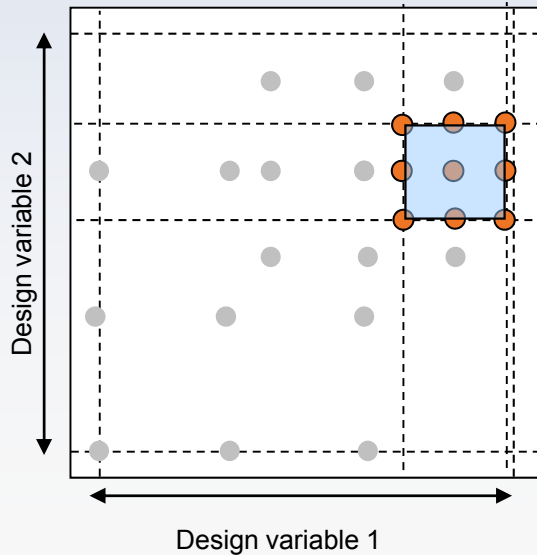
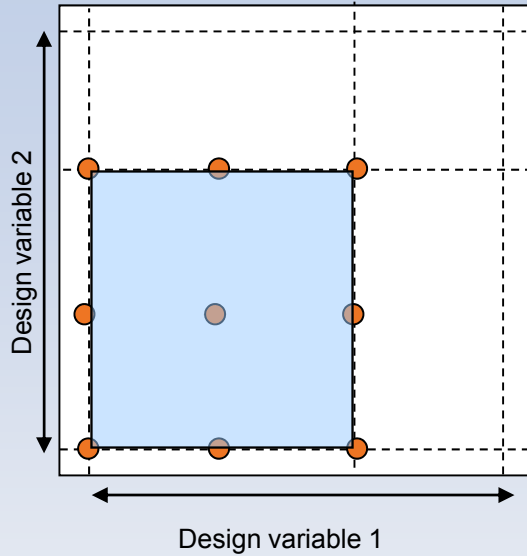


Evolutionary Algorithms (EA)

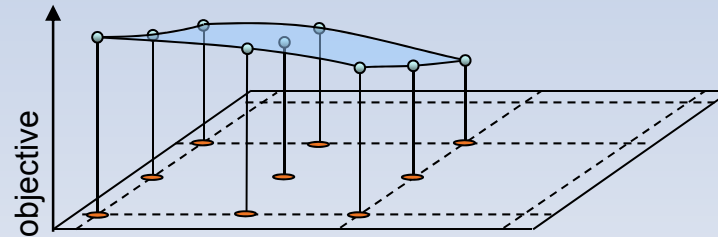


- Due to the non-convex behavior of the efficiency and nonlinear power function, a global search strategy using genetic algorithms is recommended.

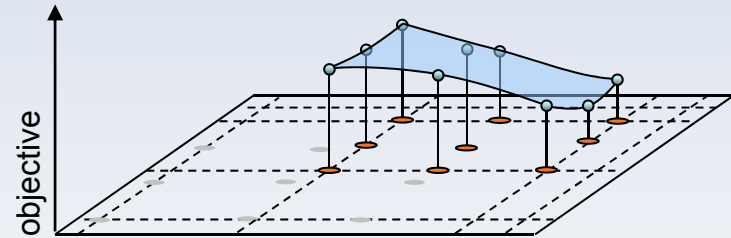
Adaptive Response Surface Methods (Local)



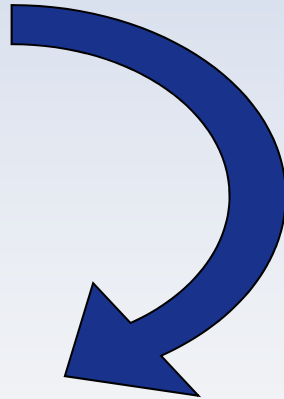
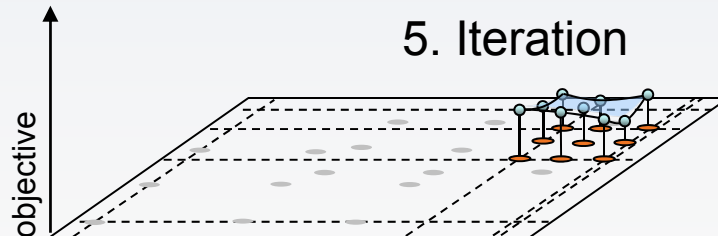
1. Iteration



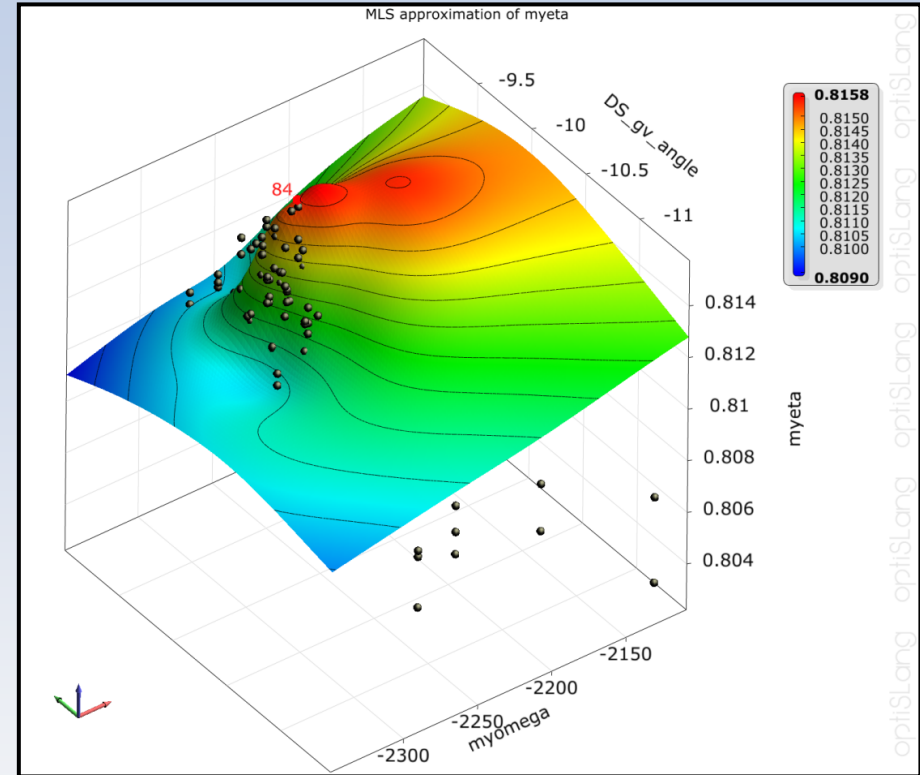
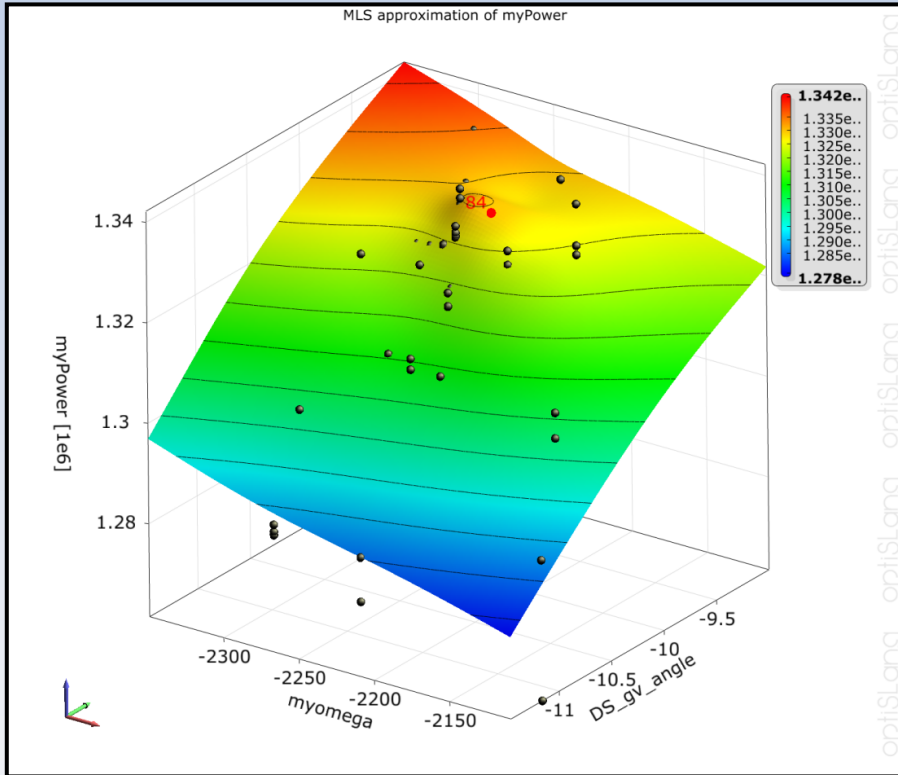
3. Iteration



5. Iteration



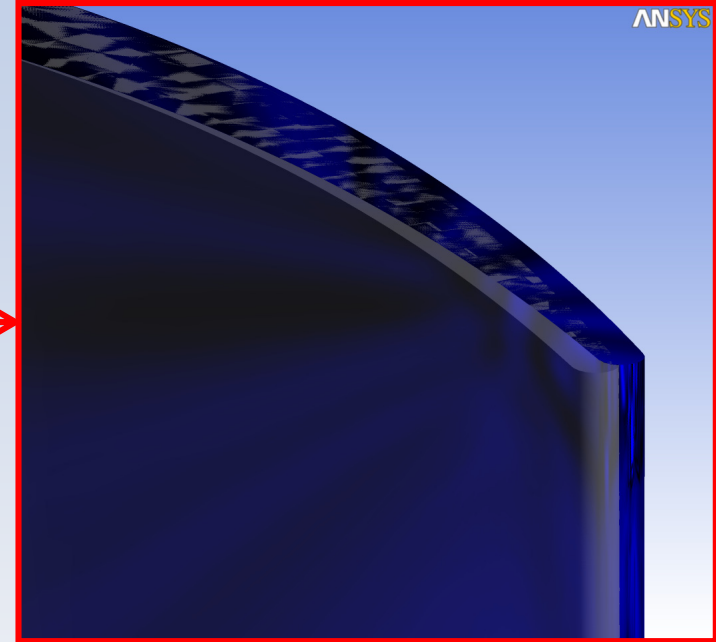
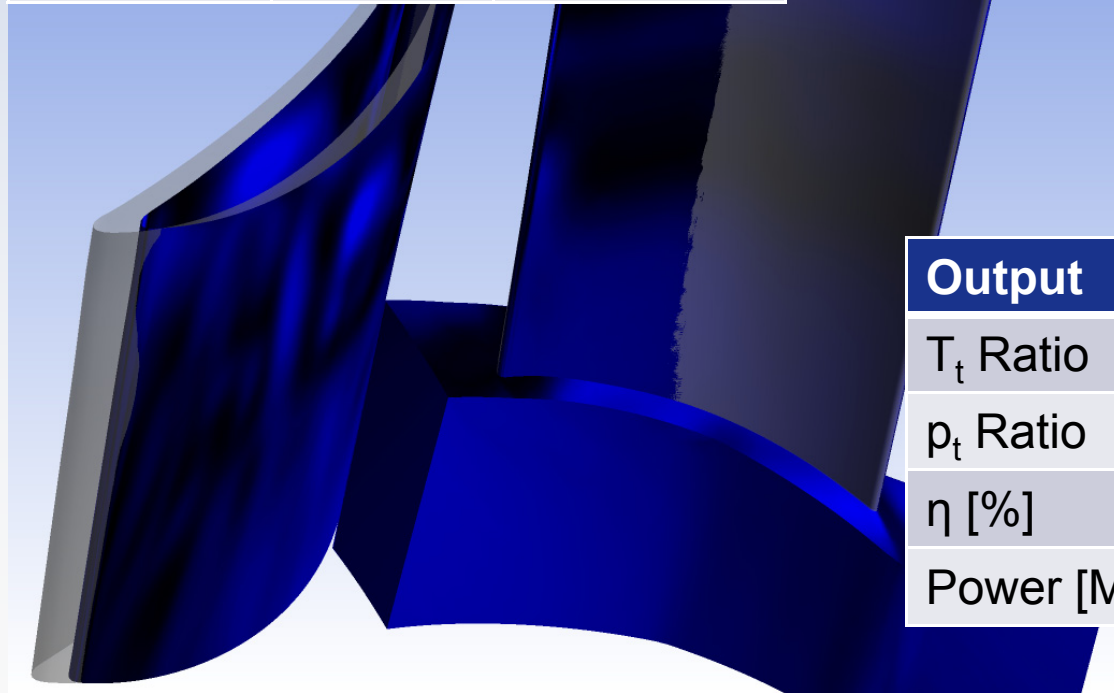
Adaptive Response Surface (ARSM)



- 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

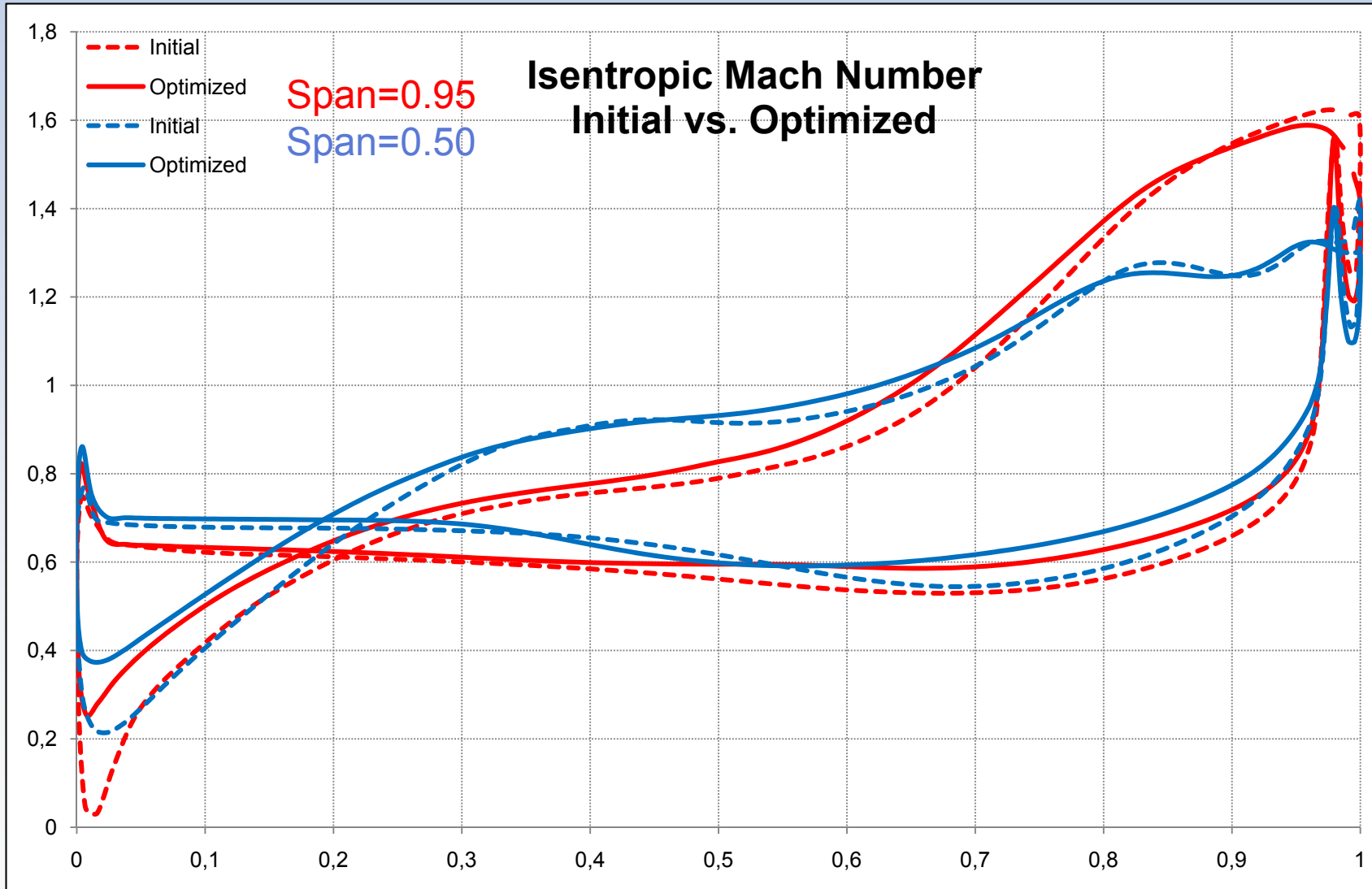
Initial vs. Optimized Design

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



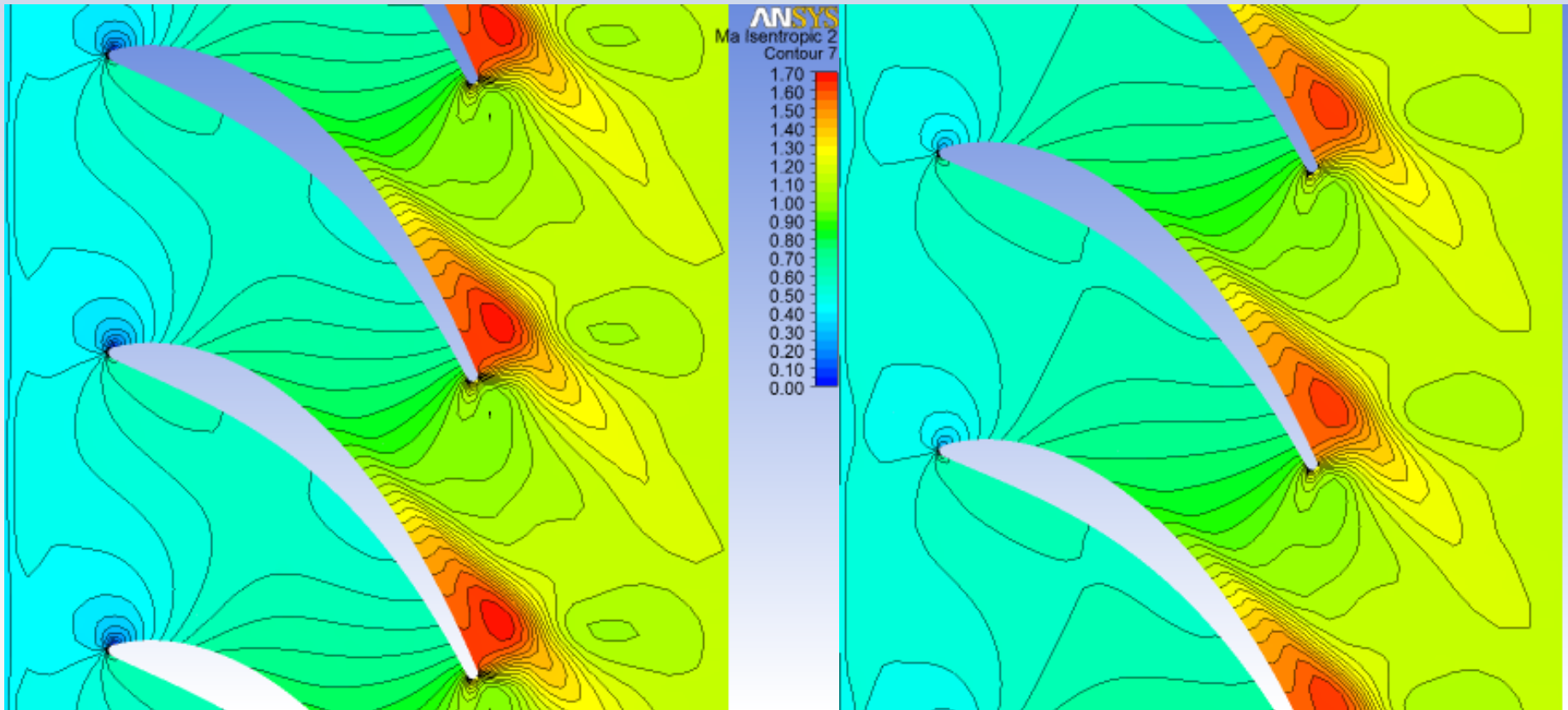
Initial vs. Optimized Design

Isotropic Mach Number

Initial

Rotor

Optimized



Initial vs. Optimized Design

Temperature
Contour 2

ANSYS
[C]

ANSYS

- $n = 7$ 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

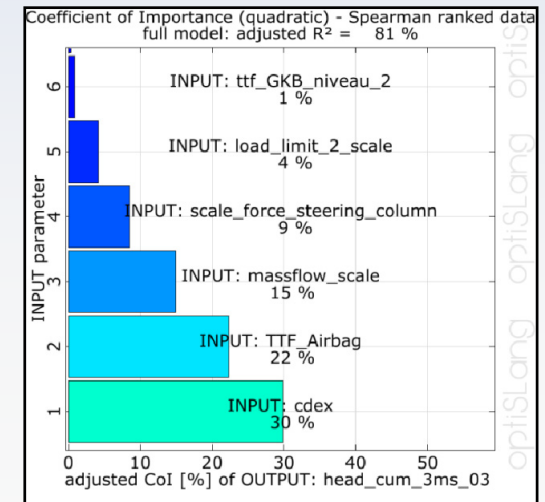
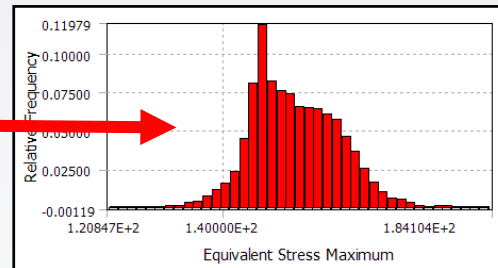
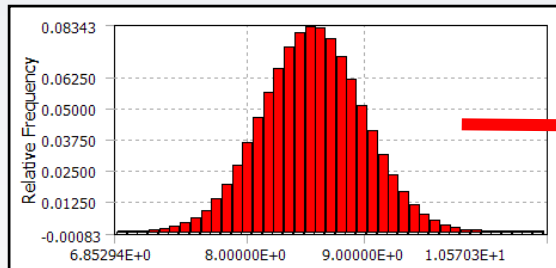
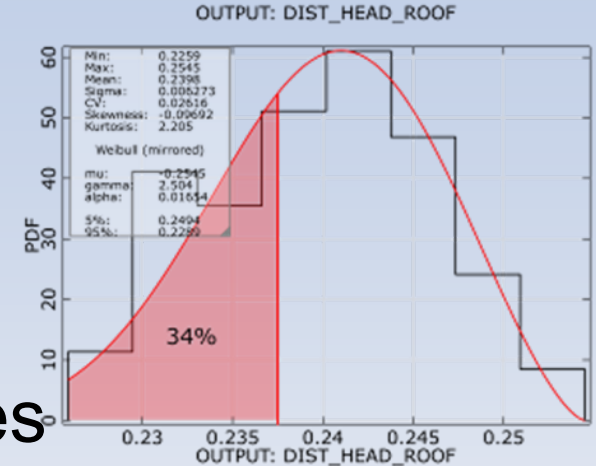
Robustness Evaluation



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

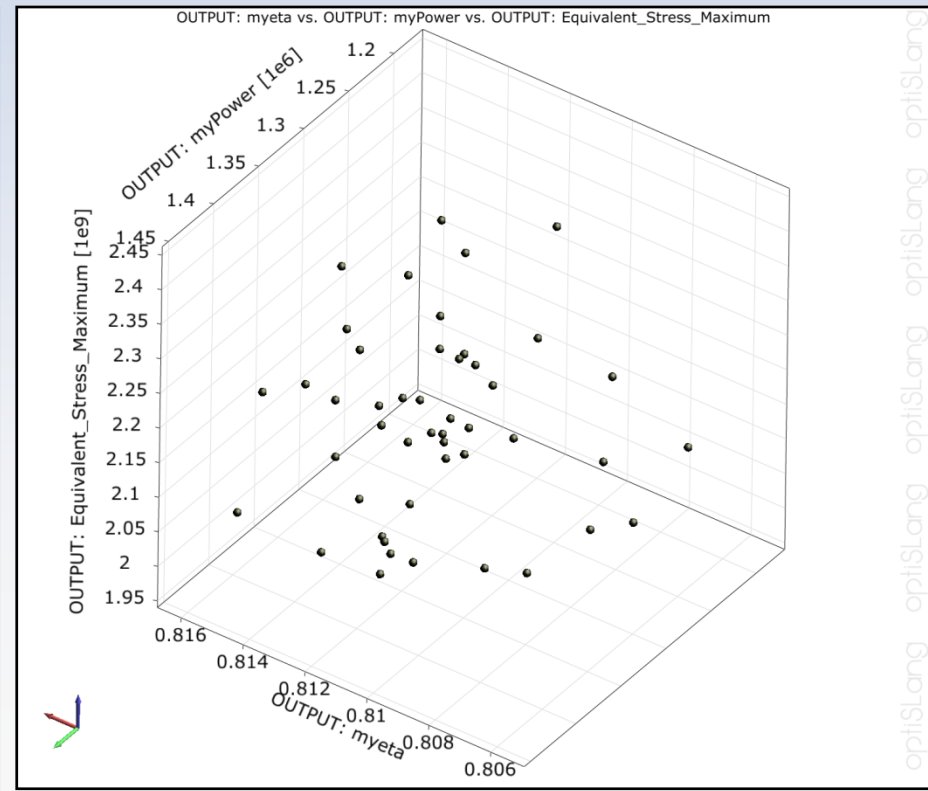
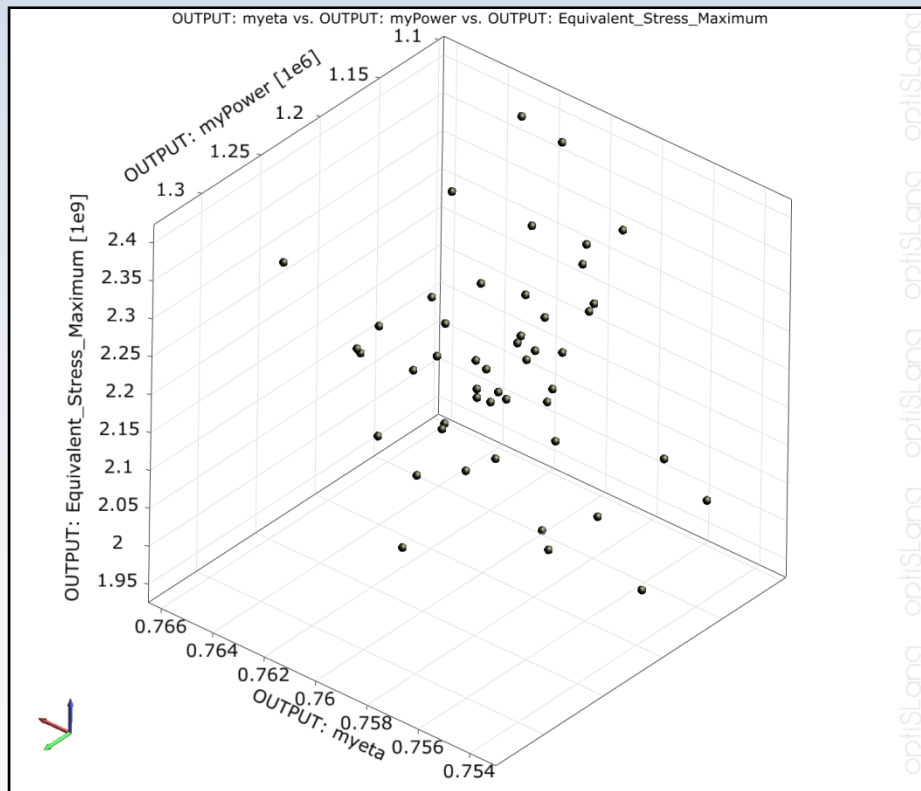


optiSlang optiSlang optiS

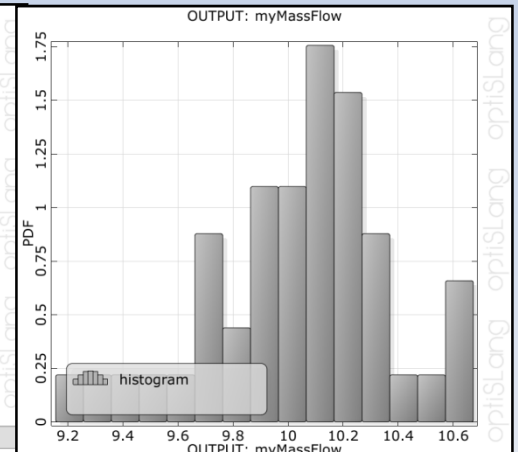
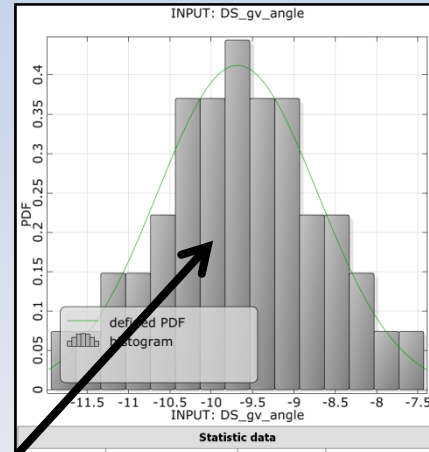
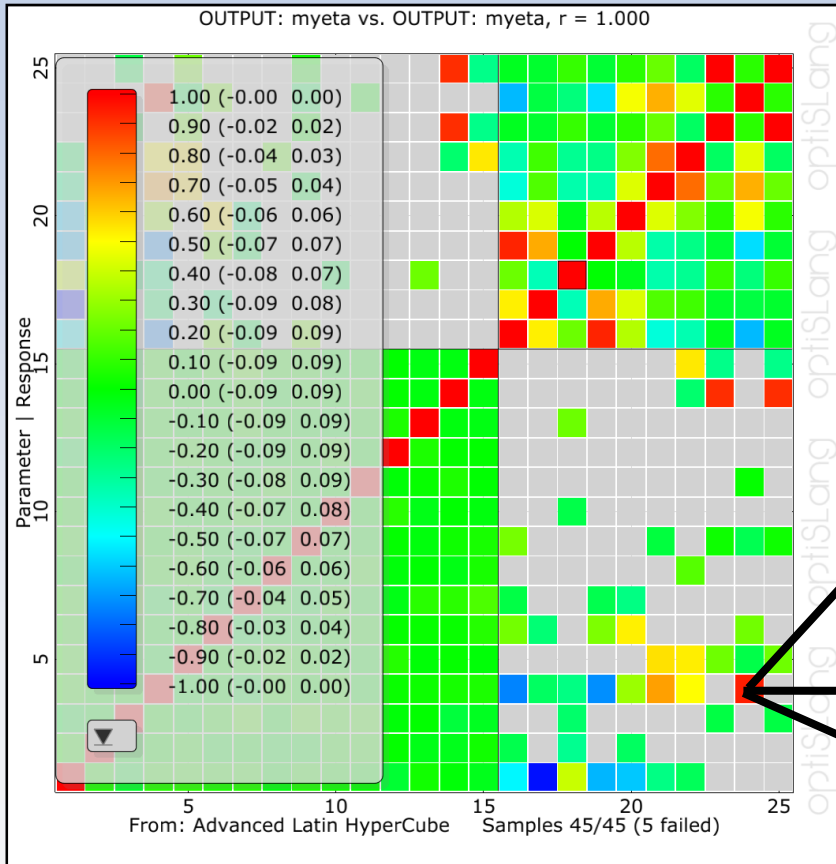
Variation of Robust Space



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



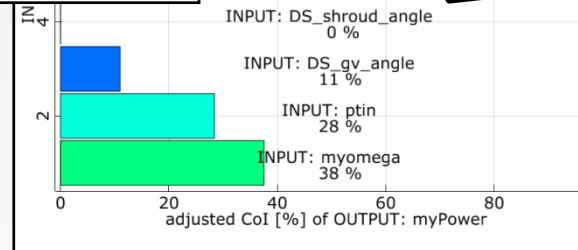
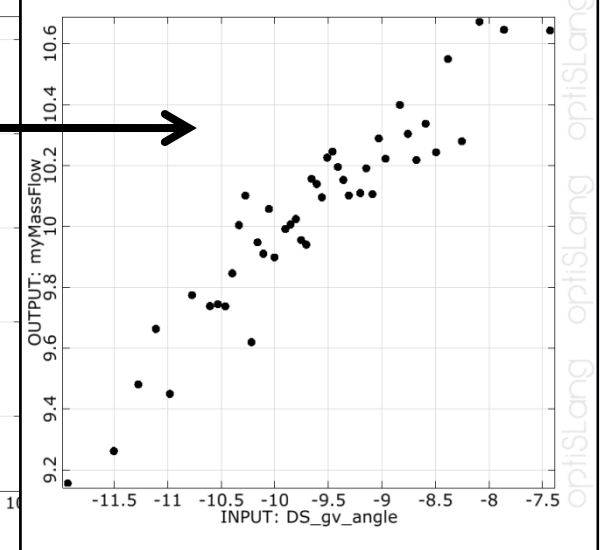
Correlation, Col, Histogram



Importance (linear) - Spearman ranked data
 Model: adjusted R² = 83 %

- INPUT: mySteelLambda 0 %
- INPUT: mySteelDensity 0 %
- INPUT: mySteelE 0 %
- INPUT: myAirR 0 %
- INPUT: myAirCP 0 %
- INPUT: Ttin 0 %
- INPUT: DS_shroud_angle 0 %
- INPUT: DS_gv_angle 11 %
- INPUT: ptin 28 %
- INPUT: myomega 38 %

INPUT: DS_gv_angle vs. OUTPUT: myMassFlow, (linear) $r_s = 0.941$

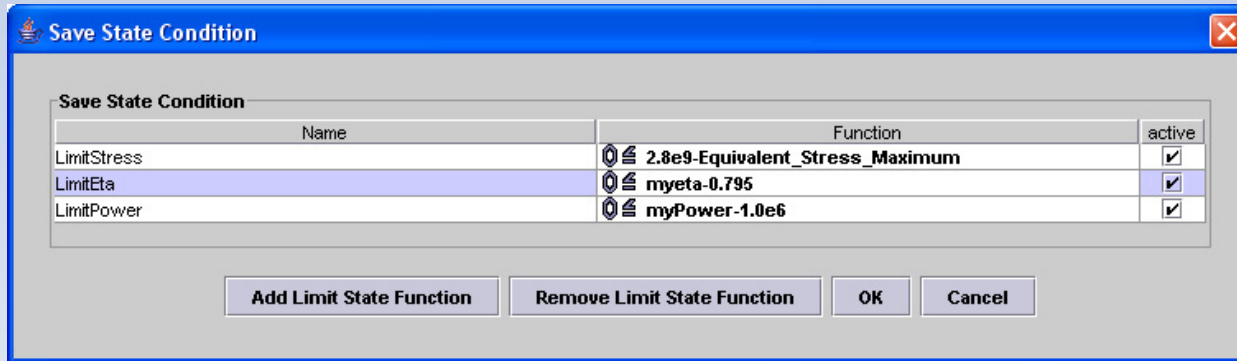


Guide vane angle
 vs. mass flow rate

Define Objective Limits



- Limit state conditions



- 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....	-	-	...	<input checked="" type="checkbox"/>
2	DS_hub_angle	Normal	0.0	Infinity	0.0...	-	-	...	<input checked="" type="checkbox"/>
3	DS_shroud_angle	Normal	0.0	Infinity	0.0...	-	-	...	<input checked="" type="checkbox"/>
4	DS_gv_angle	Normal	0.0	Infinity	0.1...	-	-	...	<input checked="" type="checkbox"/>
5	Ttin	Normal	1000.0	0.02	20.0	-	-	...	<input checked="" type="checkbox"/>
6	ptin	Normal	300000.0	0.03	900...	-	-	...	<input checked="" type="checkbox"/>
7	pout	Normal	87000.0	0.02	174...	-	-	...	<input checked="" type="checkbox"/>
8	myAirCP	Normal	1004.4	0.03	30....	-	-	...	<input checked="" type="checkbox"/>
9	myAirR	Normal	287.102	0.03	8.6...	-	-	...	<input checked="" type="checkbox"/>
10	mySteelCP	Normal	434.0	0.05	21....	-	-	...	<input checked="" type="checkbox"/>
11	mySteelDensity	Normal	7850.0	0.01	78.5	-	-	...	<input checked="" type="checkbox"/>
12	mySteelLambda	Normal	60.5	0.04	2.42	-	-	...	<input checked="" type="checkbox"/>
13	DS_FBlendRotor	Normal	1.0	0.02	0.02	-	-	...	<input checked="" type="checkbox"/>
14	Youngs_Modulus	Normal	2.0E11	0.03	6.0E9	-	-	...	<input checked="" type="checkbox"/>
15	Poissons_Ratio	Normal	0.3	0.1	0.03	-	-	...	<input checked="" type="checkbox"/>

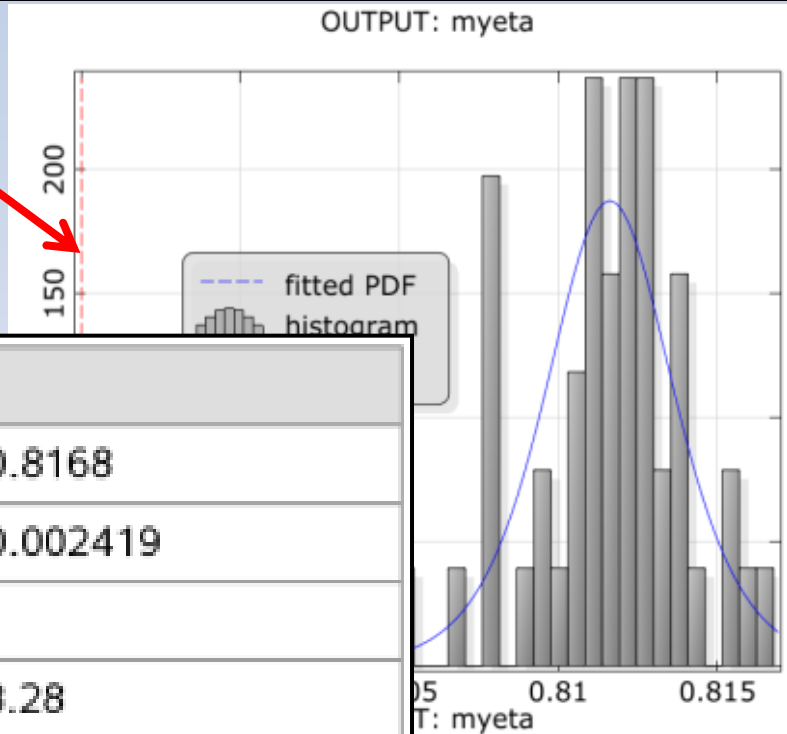
AxialTurbine_04ROBUST.pro

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

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

Statistic data	
Max:	0.8168
Sigma:	0.002419
Kurtosis:	3.28
Fitted PDF: Logistic	
Sigma:	0.002419

Limit x = 0.795	
P_rel =	0
P_fit =	3.87374e-06

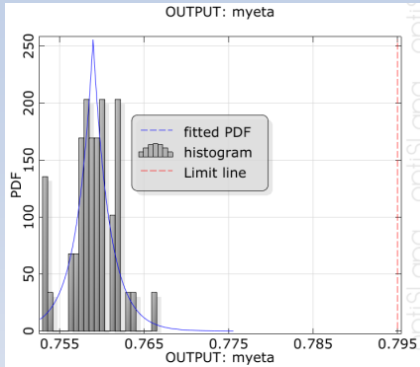
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Evaluation of Histogram

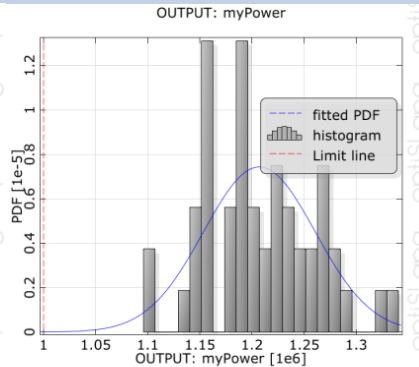


Non-robust
initial design

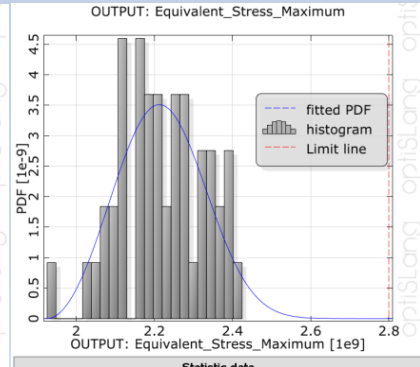
Robust
optimized
design up to a
sigma level of
4.5



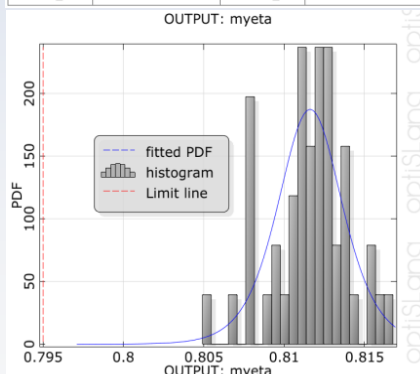
Statistic data	
Min: 0.753	Max: 0.7665
Mean: 0.759	Sigma: 0.002767
CV: 0.003645	
Skewness: -0.1759	Kurtosis: 3.679
Fitted PDF: Laplace	
Mean: 0.759	Sigma: 0.002767
Limit x = 0.795	
P_rel = 1	P_fit = 1



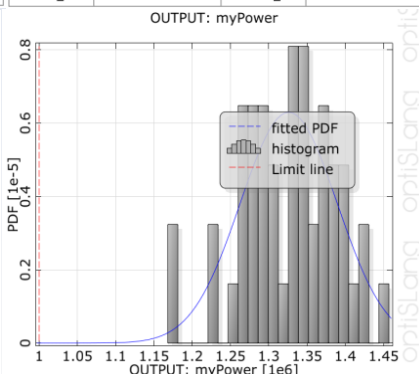
Statistic data	
Min: 1.096e+06	Max: 1.341e+06
Mean: 1.207e+06	Sigma: 5.364e+04
CV: 0.04444	
Skewness: 0.2879	Kurtosis: 2.766
Fitted PDF: Normal	
Mean: 1.207e+06	Sigma: 5.364e+04
Limit x = 1e+06	
P_rel = 0	P_fit = 5.67009e-05



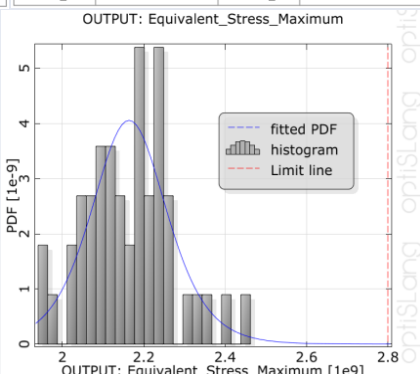
Statistic data	
Min: 1.926e+09	Max: 2.424e+09
Mean: 2.221e+09	Sigma: 1.086e+08
CV: 0.04892	
Skewness: -0.2418	Kurtosis: 2.725
Fitted PDF: Extreme Typ III (Max) Weibull	
Mean: 2.221e+09	Sigma: 1.086e+08
Lower cut: 1.926e+09	
Limit x = 2.8e+09	
P_rel = 1	P_fit = 1



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

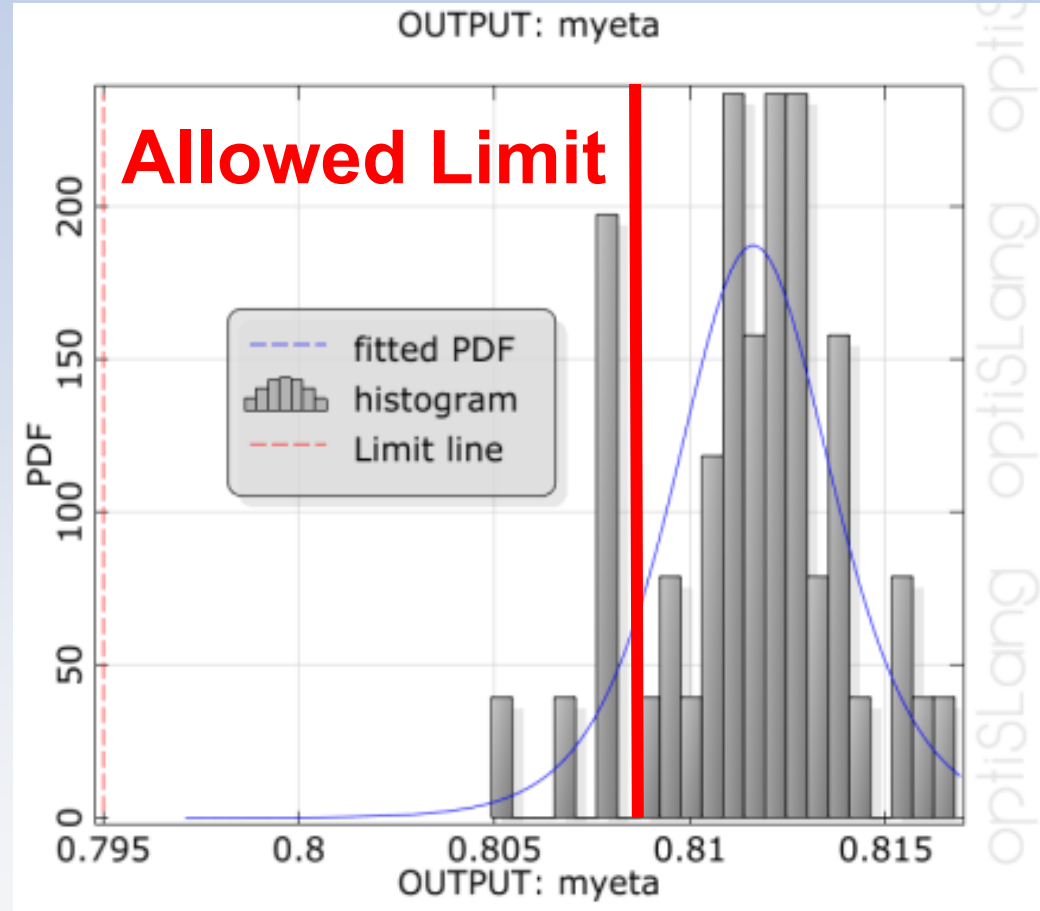
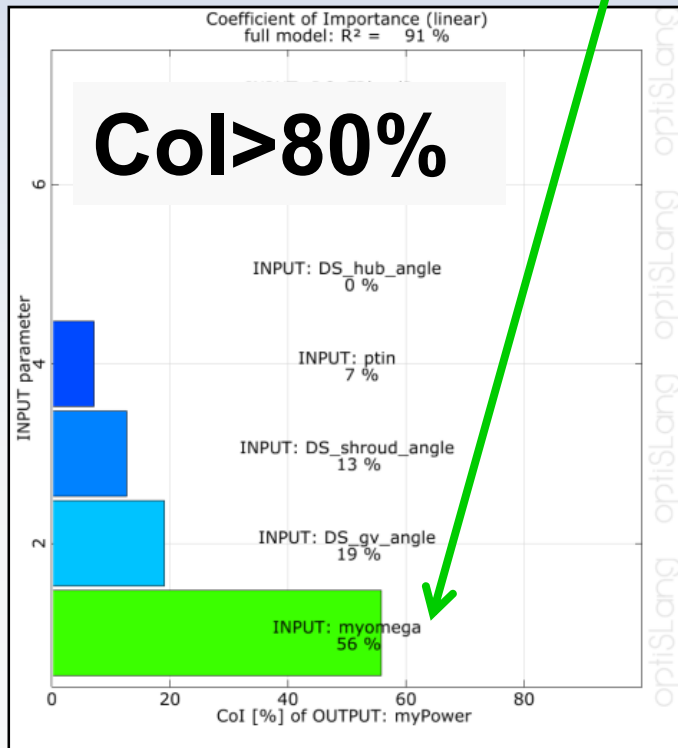


Statistic data	
Min: 1.94e+09	Max: 2.462e+09
Mean: 2.164e+09	Sigma: 1.118e+08
CV: 0.05165	
Skewness: 0.3229	Kurtosis: 3.244
Fitted PDF: Logistic	
Mean: 2.164e+09	Sigma: 1.118e+08
Limit x = 2.8e+09	
P_rel = 1	P_fit = 0.999967

Conclusion Robustness Evaluation



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





**Parameterization
Process & Geometry**

Sensitivity Analysis

Design Optimization

Robustness Evaluation

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**