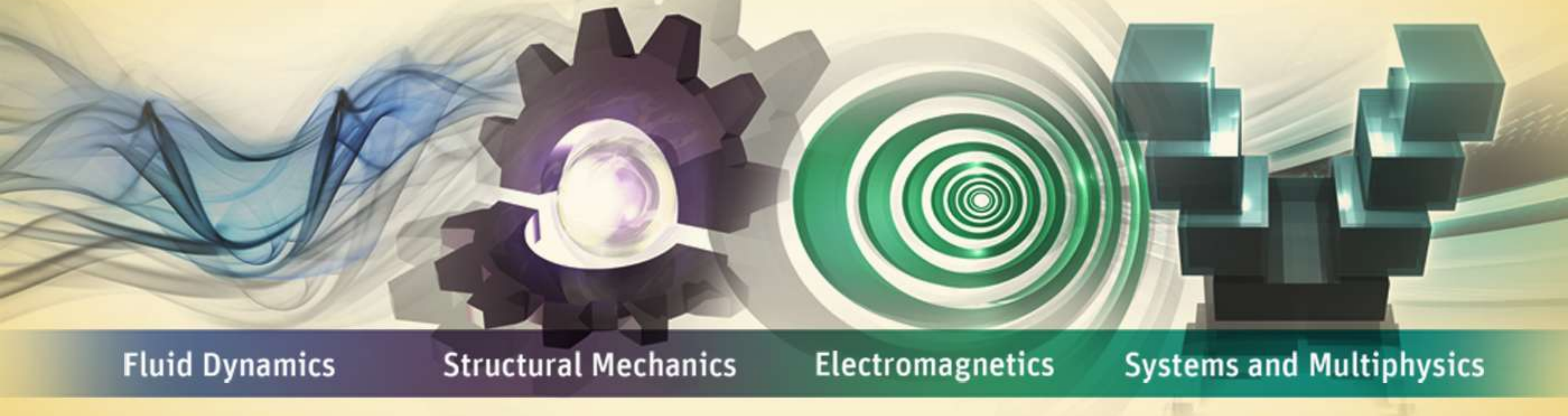
Multi-Physics Design Optimization of an Axial Compressor

Application and Best-Practice Guide-Lines

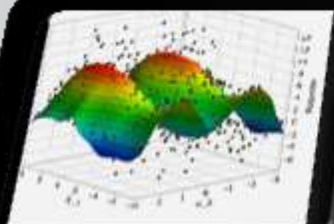


Johannes Einzinger, ANSYS

dynardo
presented at the 9th Weimar Optimization and Stochastic Days 2012
Source: www.dynardo.de/en/library

Overview

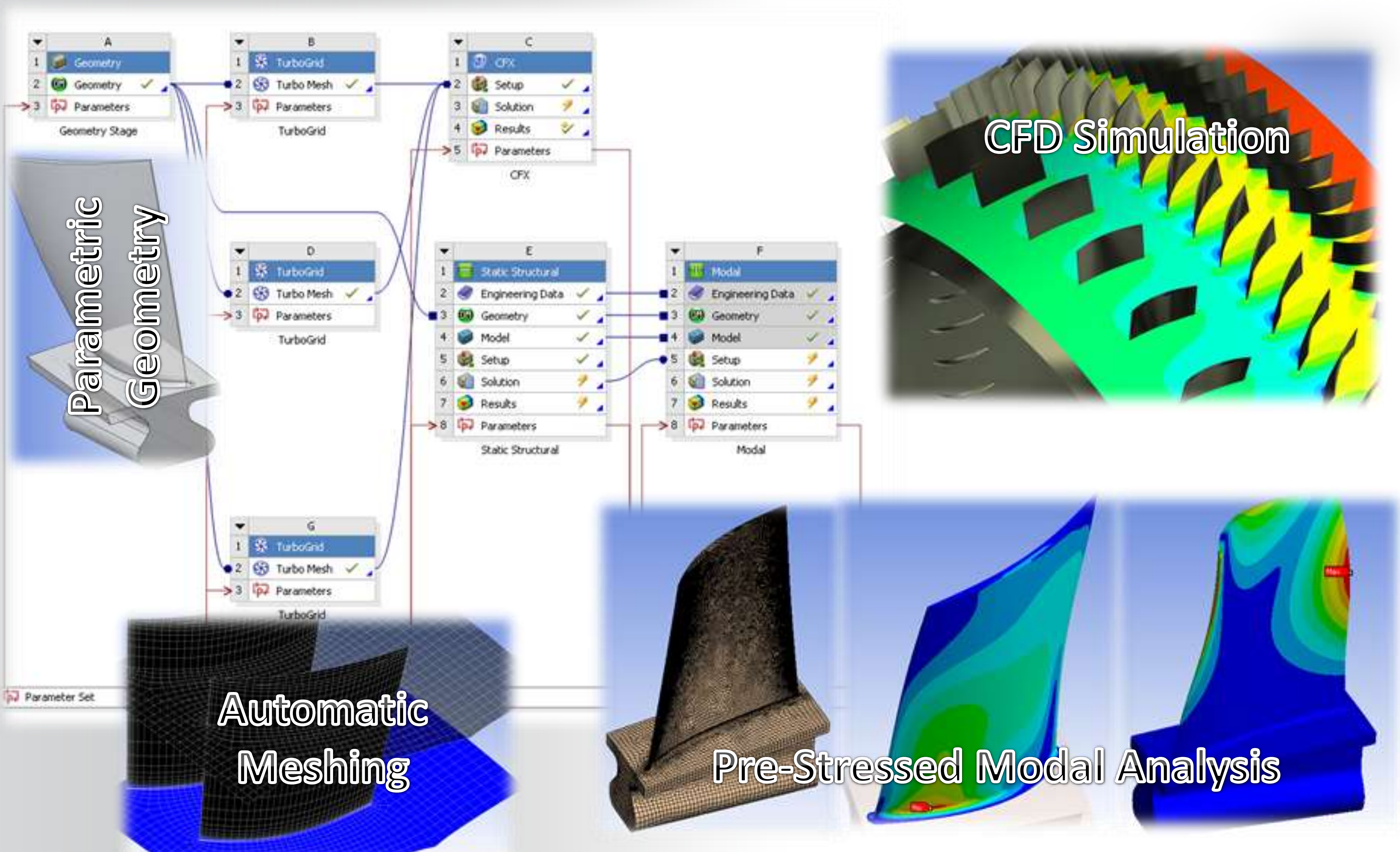
Simulation Model, Best-Practice CFD and FEM



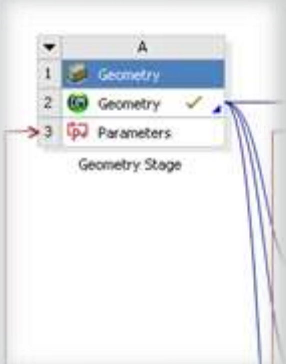
Meta-Model of optimal Prognosis

Best-Practice for MoP

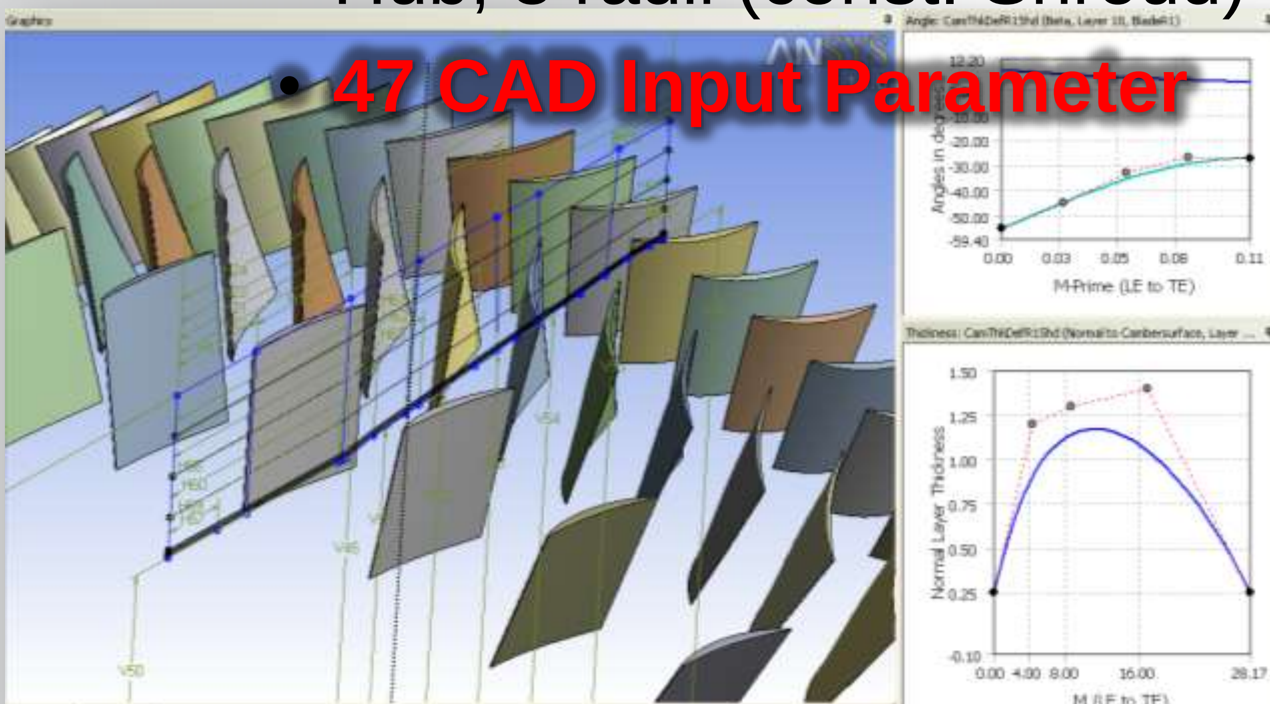
Application Overview

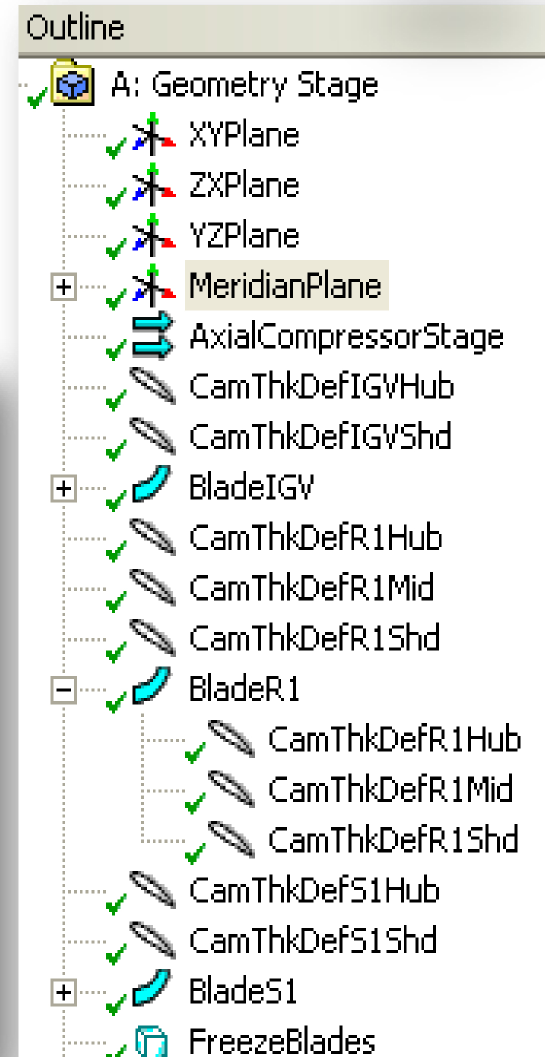


Geometry, Aero Dynamic

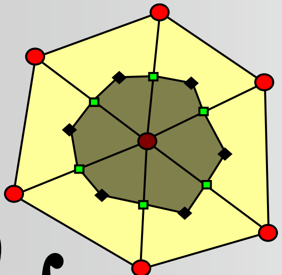


- Camber/Thickness for
  - IGV, R1, S1; 2-3 Layers
  - 5 β_i per Layer, 3xThk
- Hub, 8 radii (const. Shroud)
- **47 CAD Input Parameter**



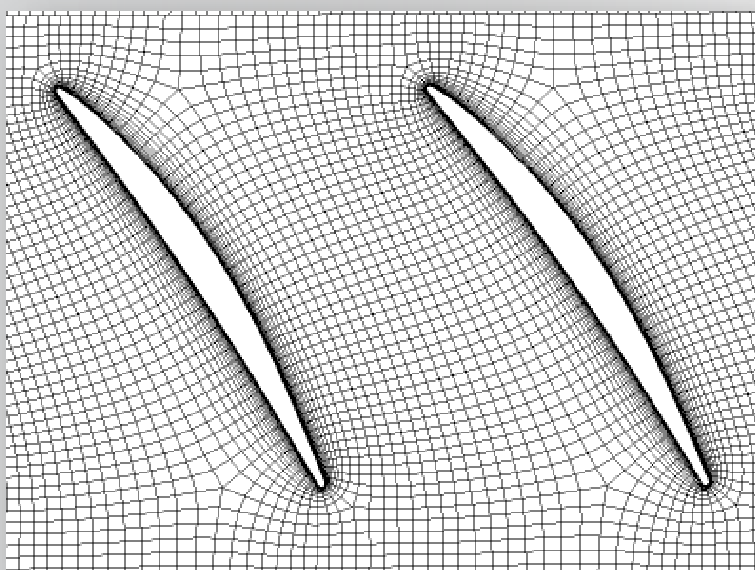


CFD Simulation



- **CFD Solver: CFX**
- **Nodal based FVM**

$$\frac{\partial}{\partial t}\int_{V} \rho\varphi \, dV + \oint_{A} \rho\varphi \mathbf{V}\cdot d\mathbf{A} = \oint_{A} \Gamma\nabla\varphi\cdot d\mathbf{A} + \int_{V} S_{\varphi} \, dV$$

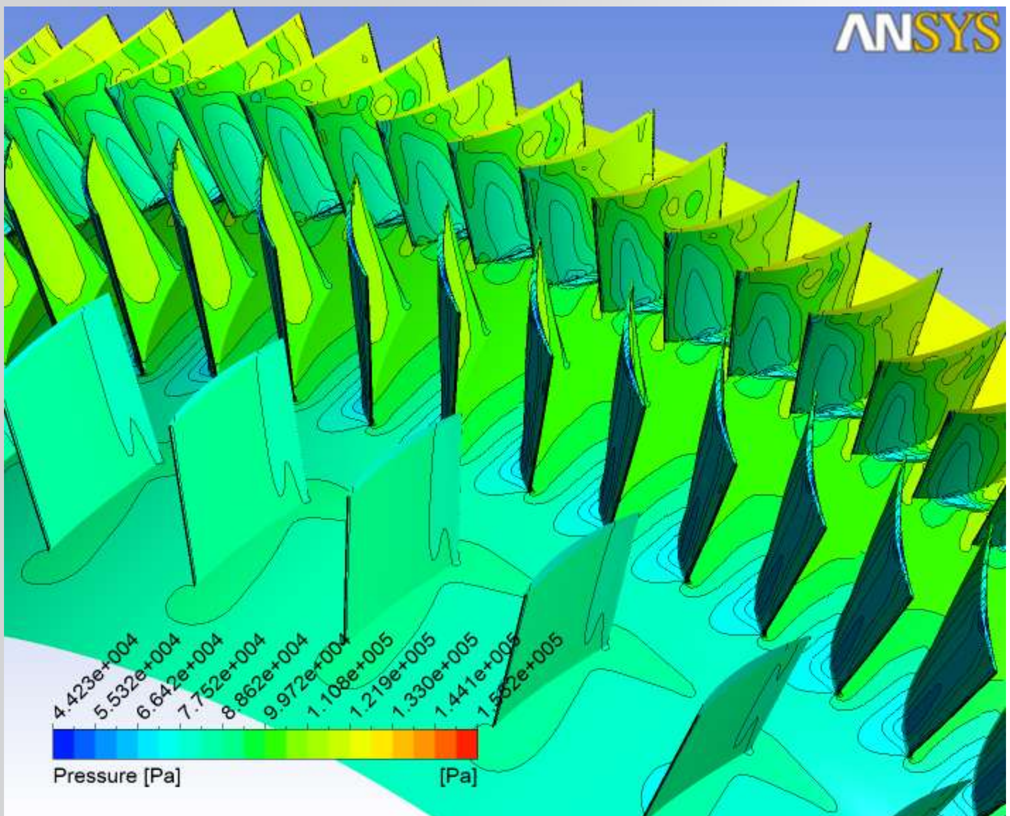


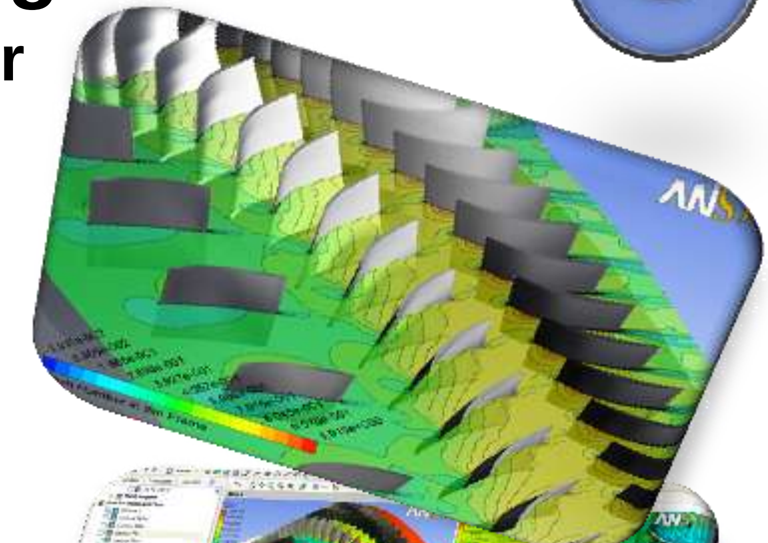
- **Coupled Solution + AMG**
  - Mass & Momentum, Energy…
- **Turbulence Model:**
  - Shear Stress Transport

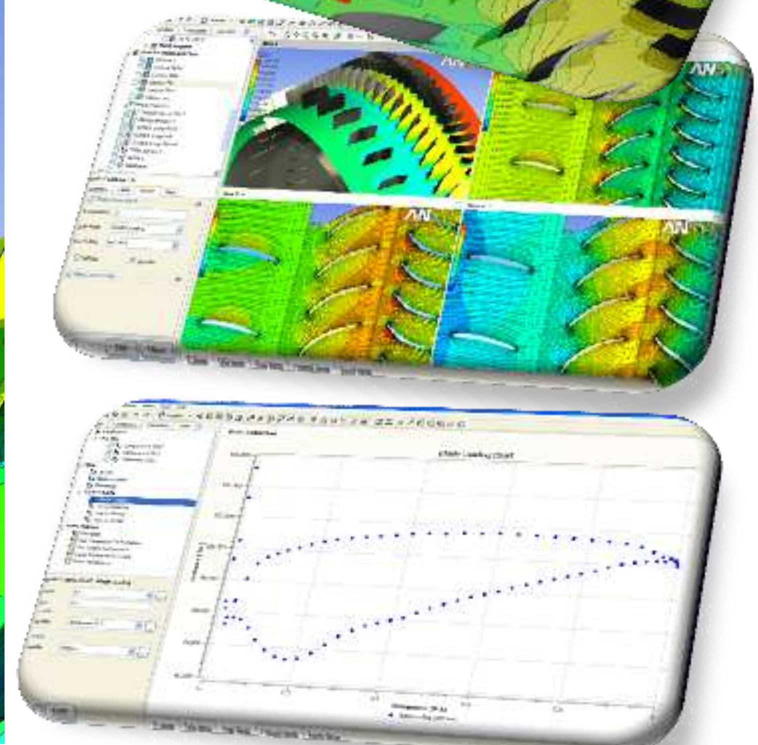
– **Two sector by passage, MFR:**
  - Profile/Time Transformation
  - Periodic Interface

CFD Post Processing

- General Post-Processor
- Turbo Mode
- Highly Automated
- Customize able

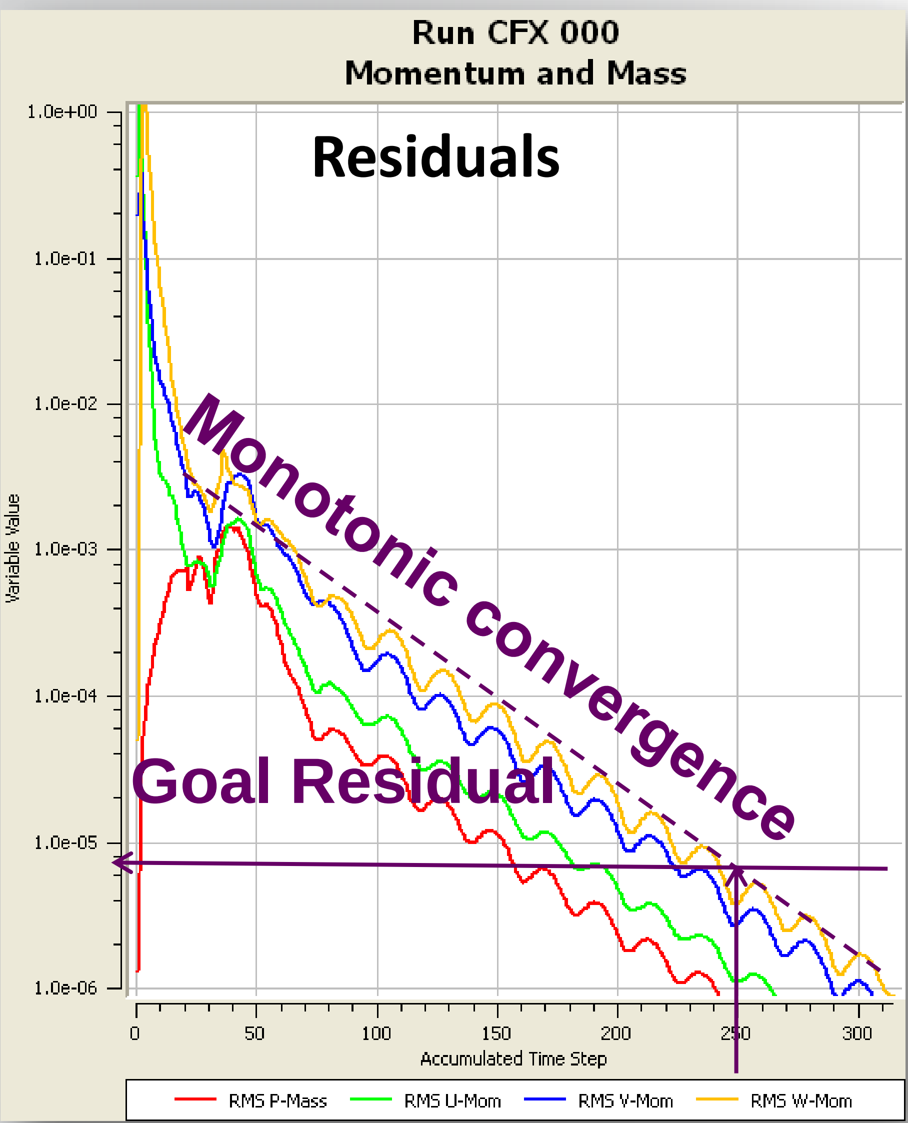


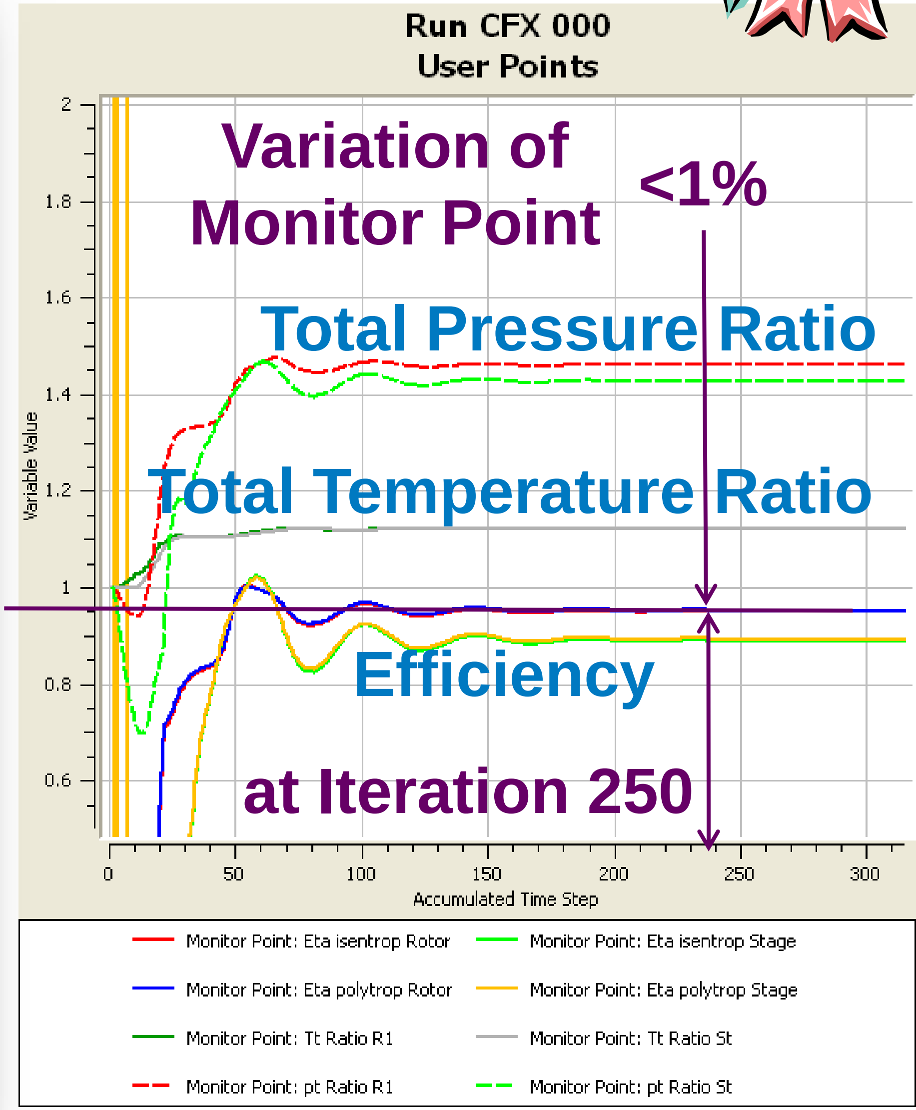




  December 11, 2012

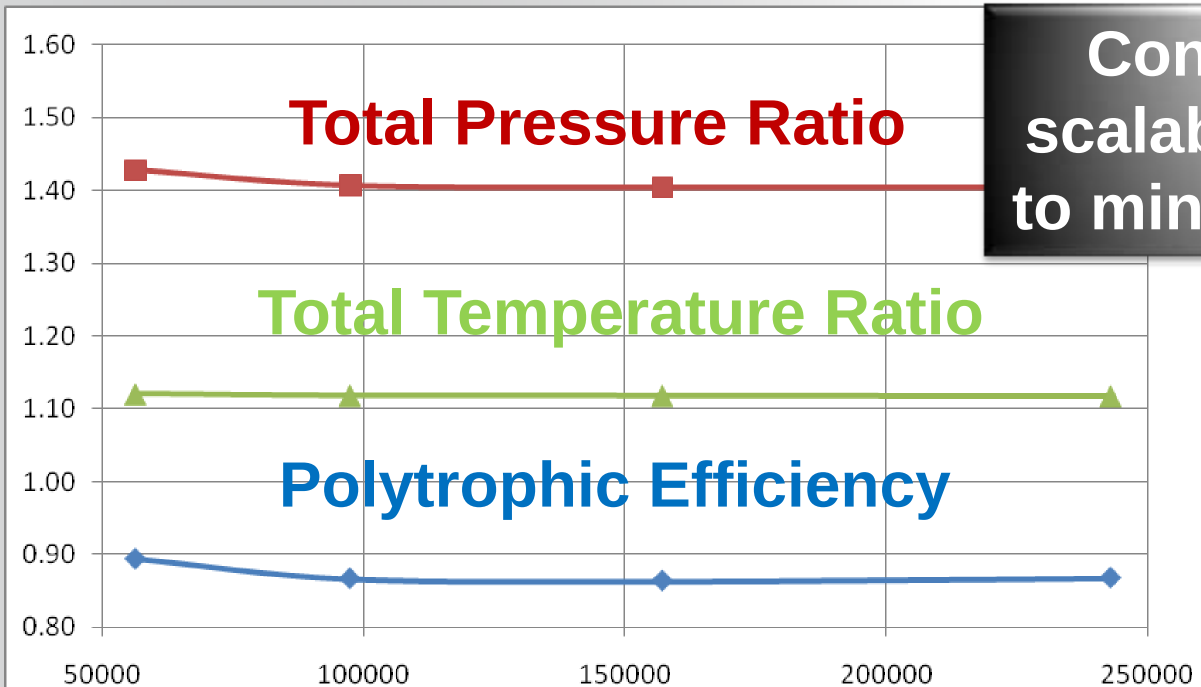
Iteration Error



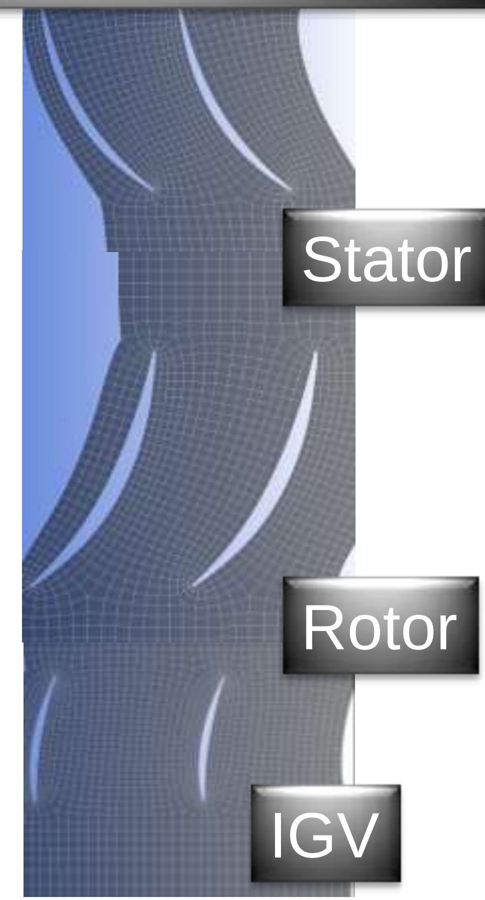


Discretization Error

Convergence study on scalable high quality mesh to minimize numerical error

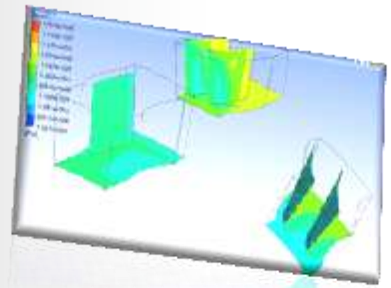


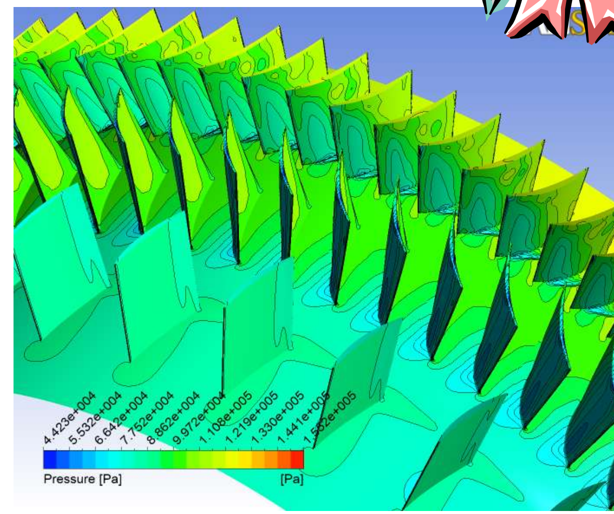
Mesh	Min Angle	Max Exp.	#Nodes
1	29.59	15.2	~50000
2	30.85	6.69	~100000
3	31.52	4.90	~150000
4	35.73	4.60	~250000



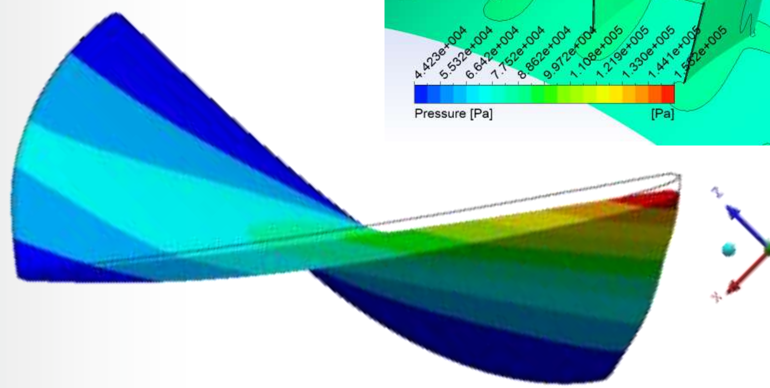
Model Error

- **Steady vs. Transient simulation**

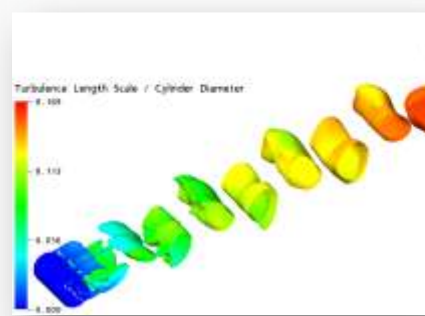


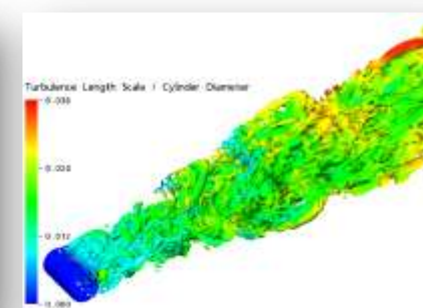


- **Cold vs. hot geometry**



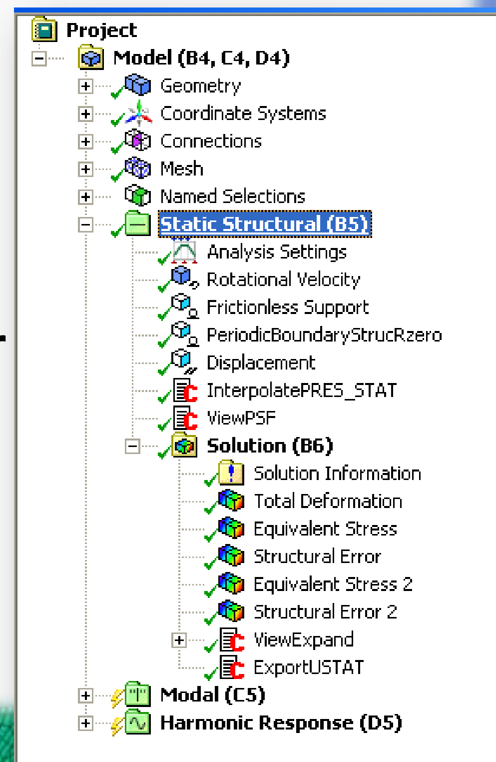
- **Turbulence Model: RANS vs. Scale Resolved**

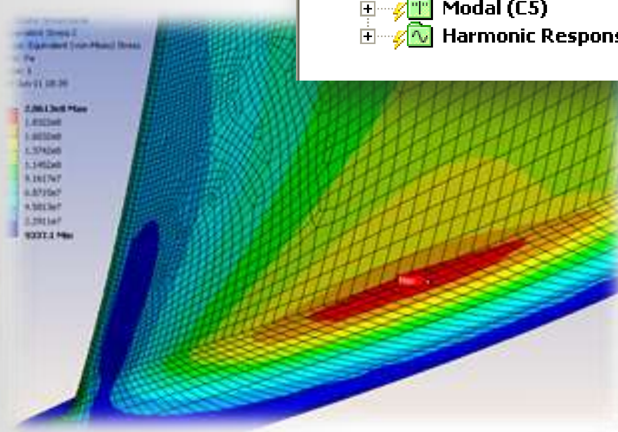


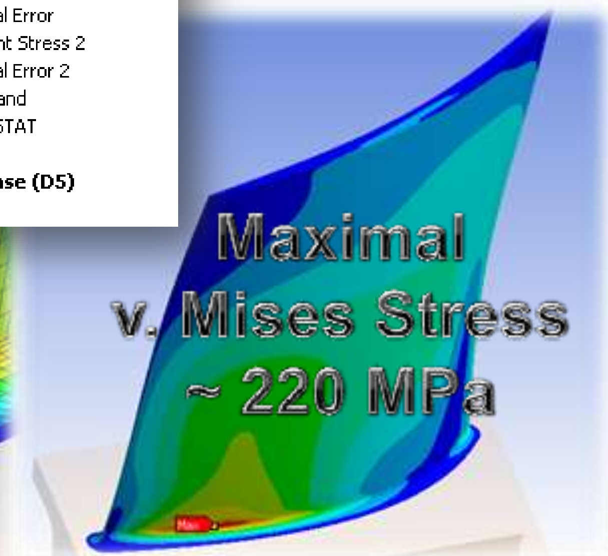


Static Structural (Pre-Stress)

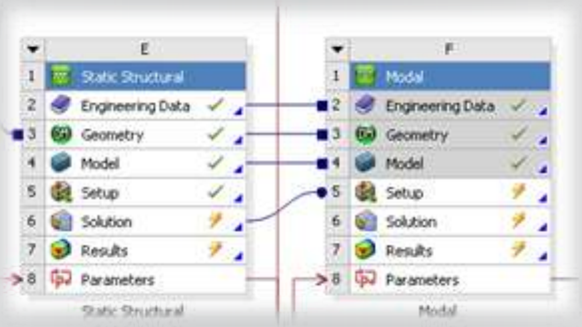
- Static Solution:
  - Displacement
  - Strain & Stress
  - Numerical Error
  - Pre-Stress for further Analysis





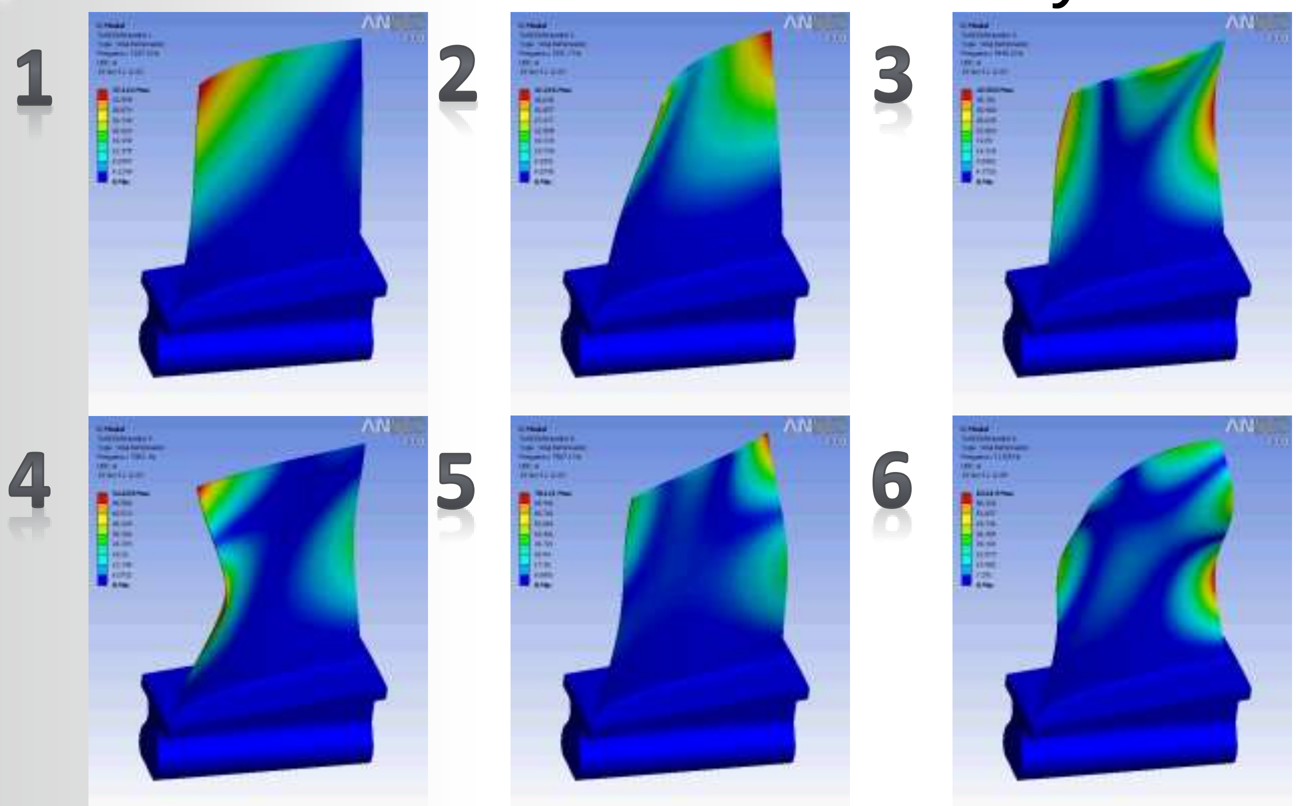


Modal Analysis



	Mode	✔ Frequency [Hz]
1	1.	1537.3
2	2.	2931.7
3	3.	5448.2
4	4.	7053.
5	5.	7567.1
6	6.	11155

- Pre-Stressed Modal Analysis:
  - Eigen Frequencies and Vectors
  - Data for further MOR-Analysis



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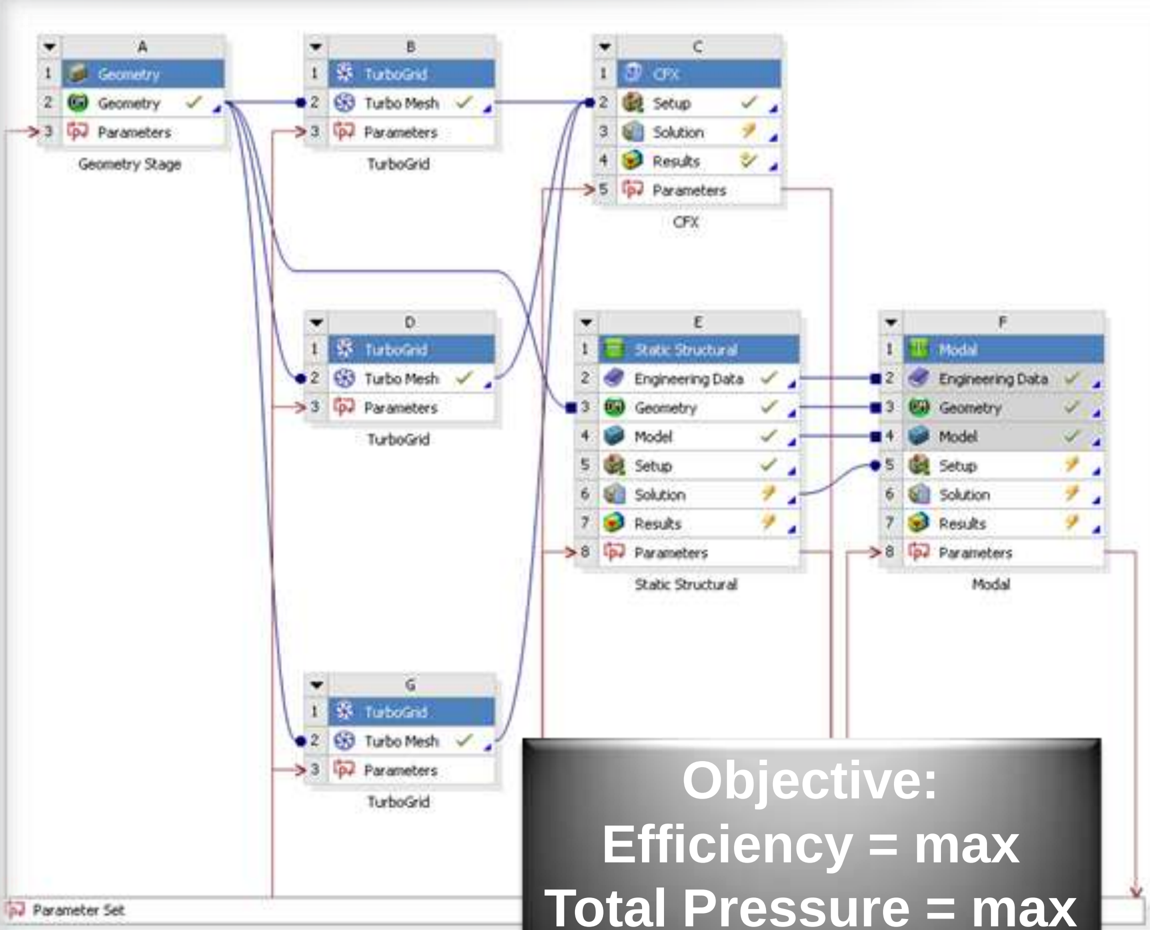
Process and Objectives



Objective:
Efficiency = max
Total Pressure = max
Stress < Limit
No Resonance

Input Parameters	
Geometry Stage (A1)	
TurboGrid (B1)	
TurboGrid (D1)	
TurboGrid (G1)	
CFX (C1)	
P16	nPitchS1
P15	nPitchR1
P14	nPitchIGV
P17	myAirCP
P18	myAirR
P19	myomega
P20	mymass
P21	Ttin
P22	ptin
Static Structural (E1)	
P89	Face Sizing Element Size
P90	Mesh Max Size
P91	Mesh Min Size
P92	Mesh Max Face Size
P93	Rotational Velocity Z Component
P94	ViewExpand ARG1
P111	Density
P112	Young's Modulus
P113	Poisson's Ratio
Modal (F1)	
New input parameter	New name
Output Parameters	
Charts	

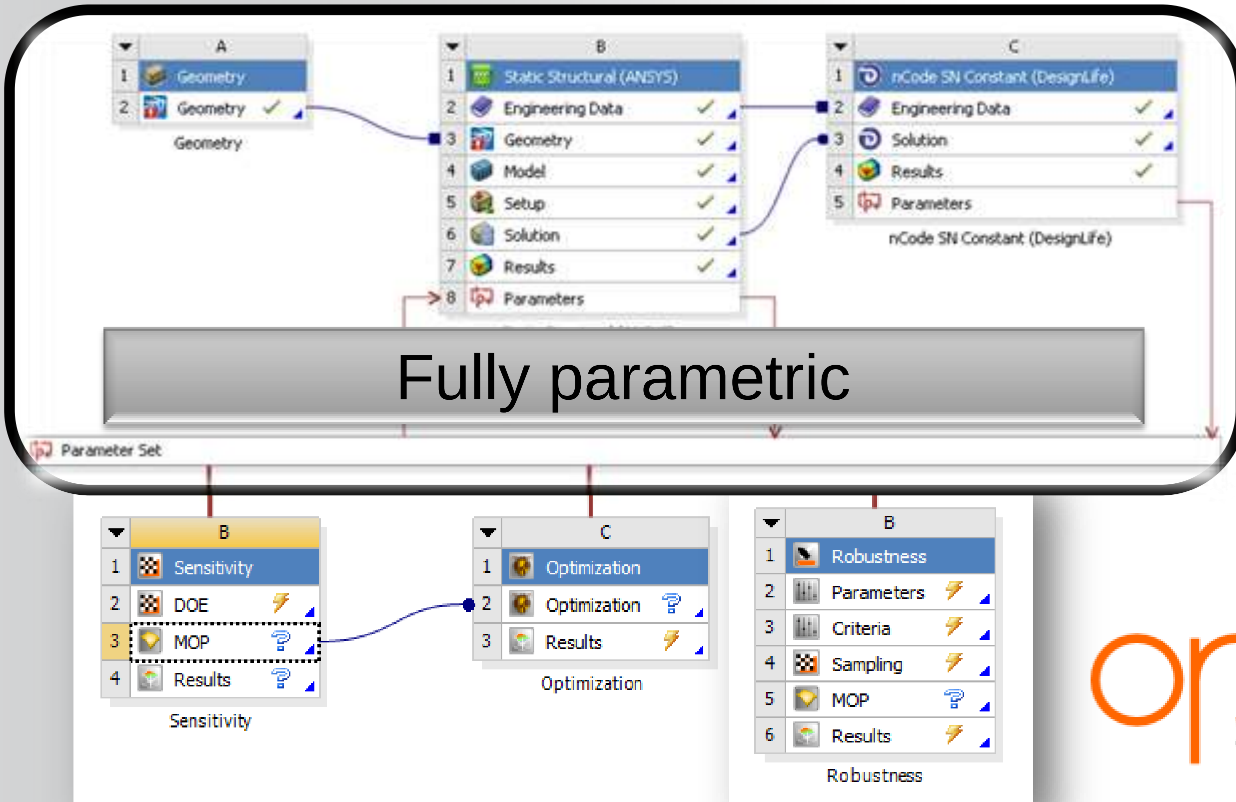
47 (59) Input Parameter

11 Input Constraints

24 Output Parameter

optiSLang inside Workbench

The Workbench Effect – easier to use



Fully parametric

Easy parametric set up of complex simulations

optiSLang
optimizing structural language

easy use of best praxis automated flows inside Workbench

Optimization Strategy

General Procedure:

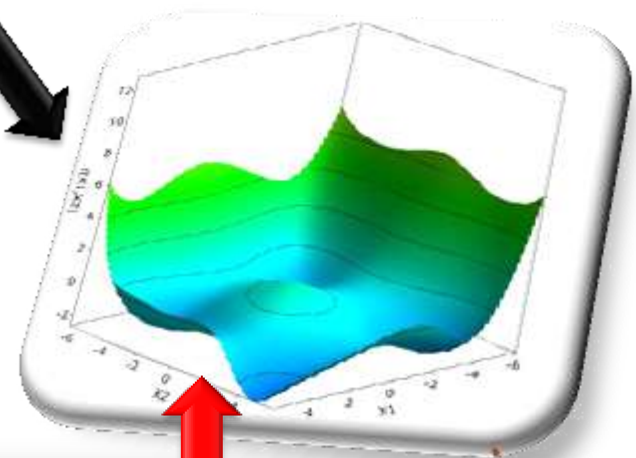
- Design Optimization
  - Gradient Based
  - Generic
  - Evolutionary
  - …

- Design of Experiments
  - Data Sampling
  - Detecting Correlations
  - Detecting Important Parameters
  - Parameter Space Reduction
  - Response Surface
- Design Optimization
  - …

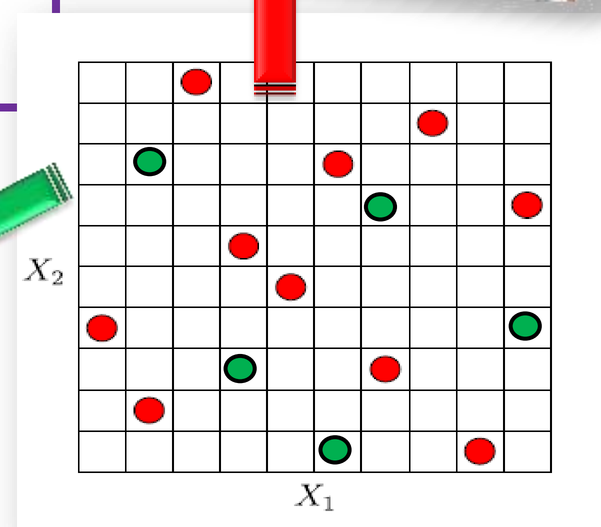
Meta-Model of Optimal Prognosis, MoP

$$Y_k = f(x_1, \cancel{x_2}, \cancel{x_3}, \cancel{x_4}, \cancel{x_5}, x_6, \cancel{x_7}, x_6, \dots, x_N)$$

- Correlation Filter
- Importance Filter (CoI)
- Remaining parameters are used for non/linear approximation
- Basic Points for Approximation
- Test Points for Quality Assurance



Data-Split

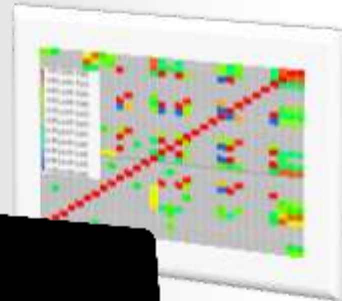


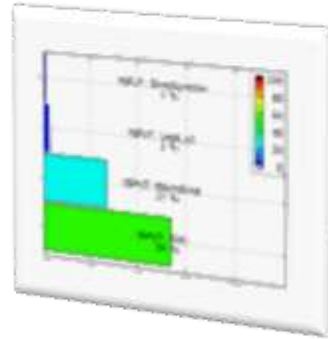
$$CoP = \left(\frac{E\left(Y \cdot \hat{Y}\right)}{\sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2 = \left(\frac{\sum_{k=1}^{N} \left(y^{(k)} - \mu_y\right) \cdot \left(\hat{y}^{(k)} - \mu_{\hat{y}}\right)}{(N-1) \cdot \sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2$$

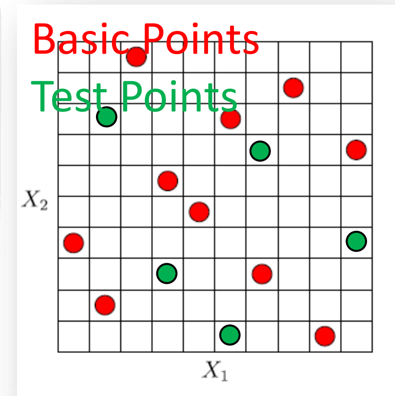
Meta-Model of Optimal Prognosis, MoP

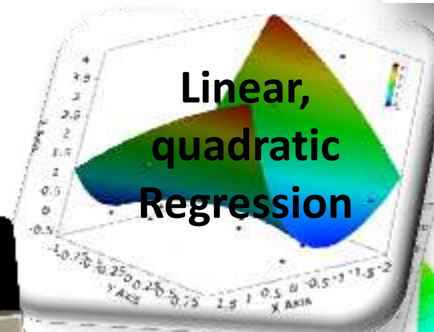
- Significance Filer
- Importance Filter
- Test-Data Point Split
- Response Surface
- Coefficient of Prognosis

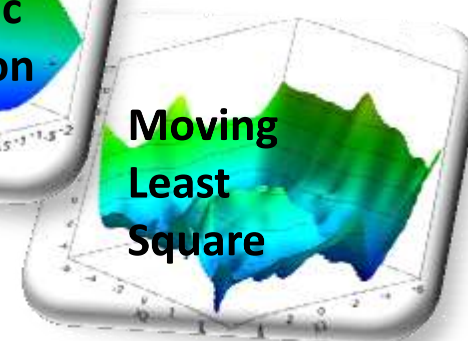
Variation of Filter Limits…





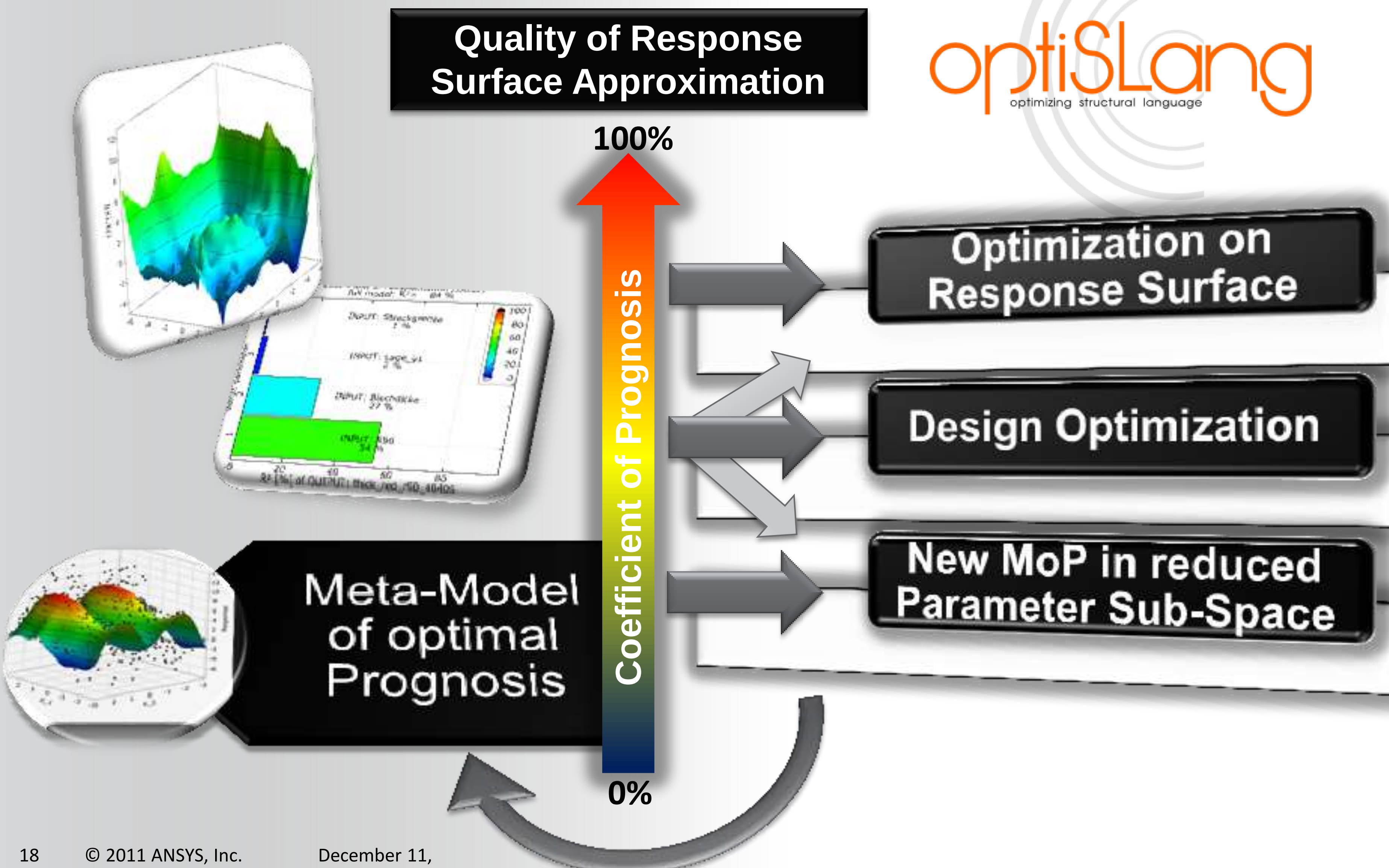




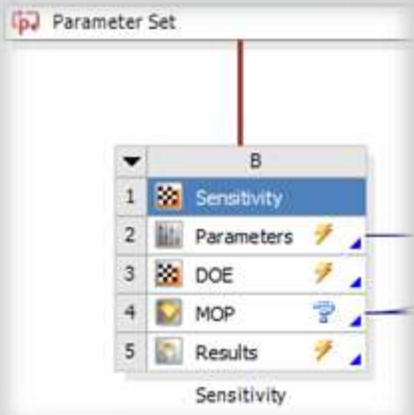


$$CoP = \left(\frac{E\left(Y \cdot \hat{Y}\right)}{\sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2 = \left(\frac{\sum_{k=1}^{N} \left(y^{(k)} - \mu_y\right) \cdot \left(\hat{y}^{(k)} - \mu_{\hat{y}}\right)}{(N-1) \cdot \sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2$$

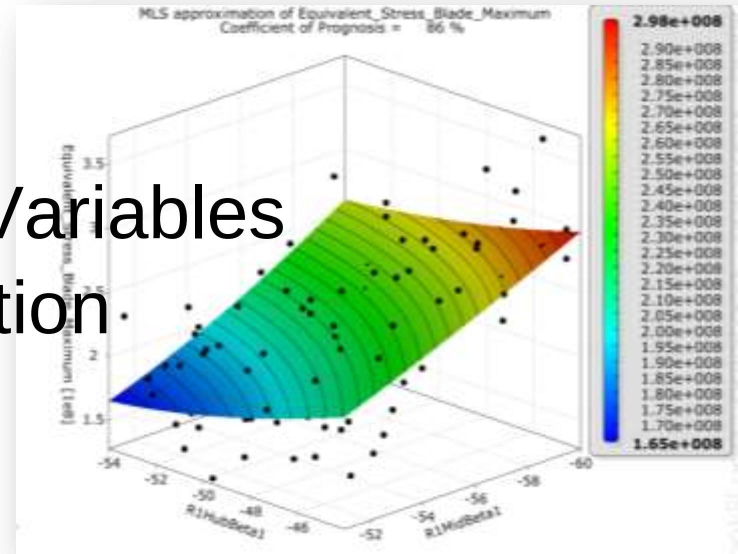
optiSLang Strategy

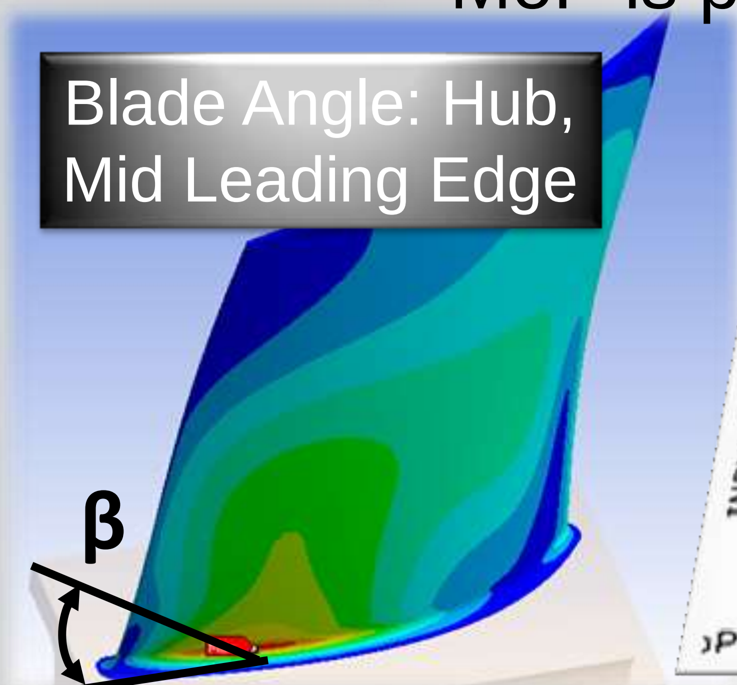


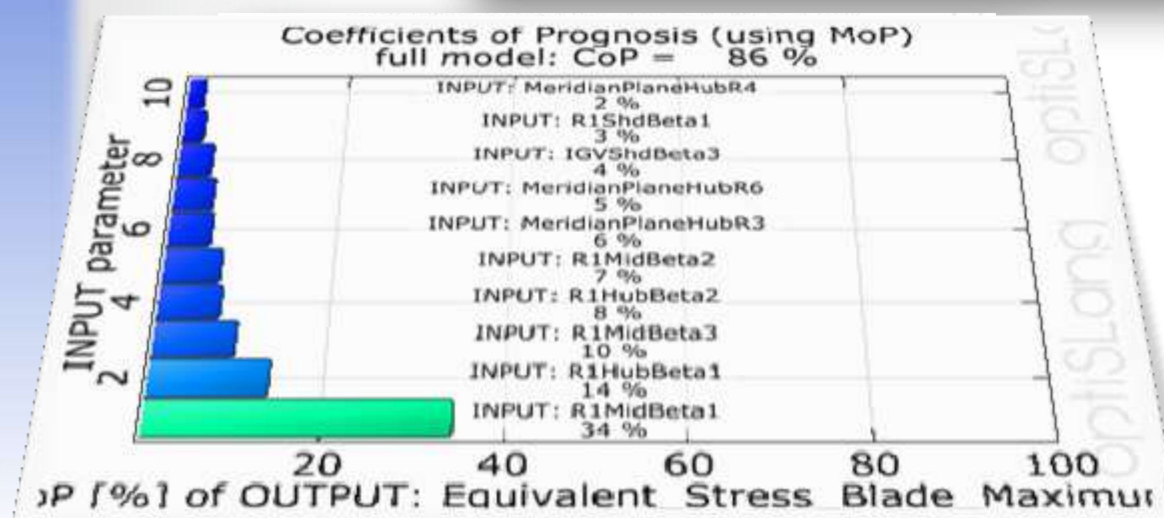
Maximal Stress



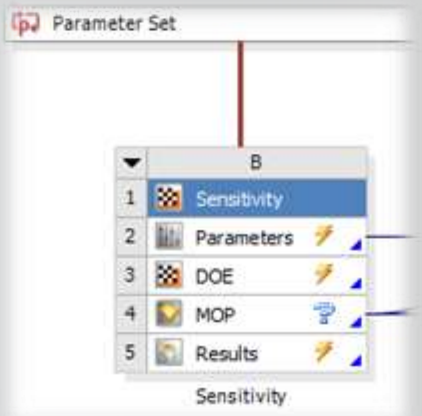
- CoP=86%
  - Statistic is reliable
  - Detect important Variables
  - Parameter Reduction
- MoP is plausible

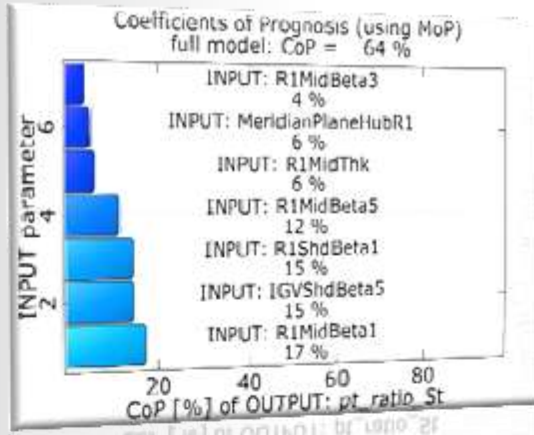


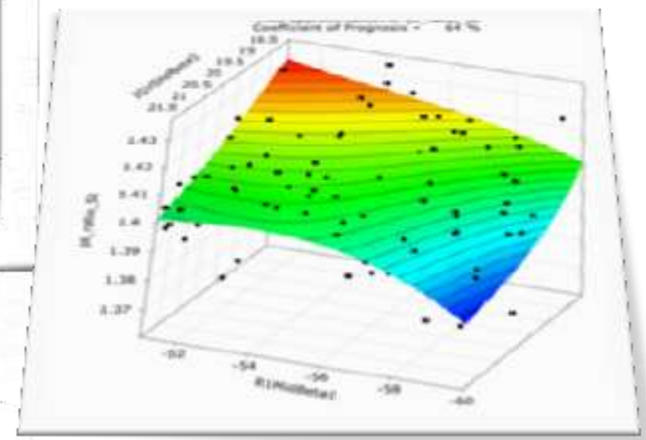


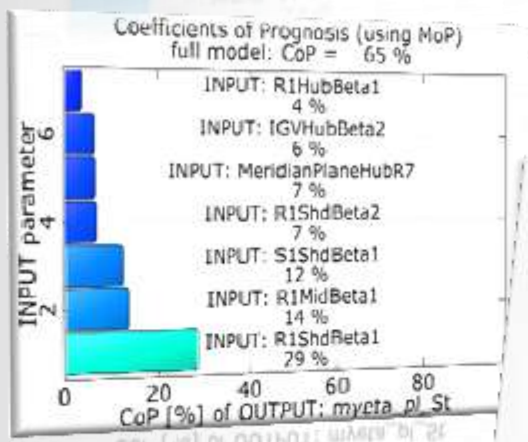


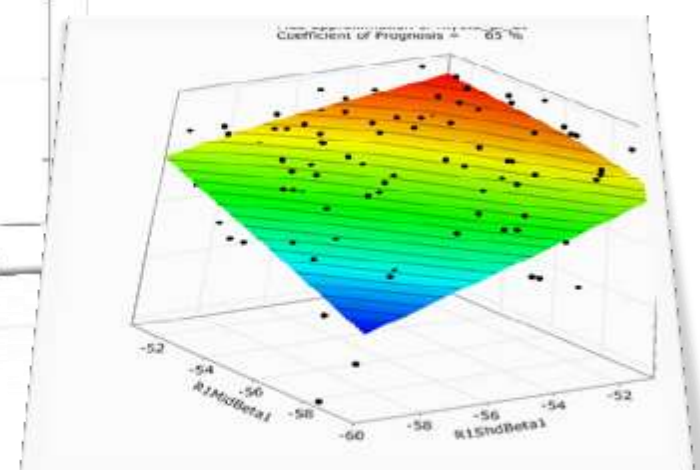
Aero Dynamic





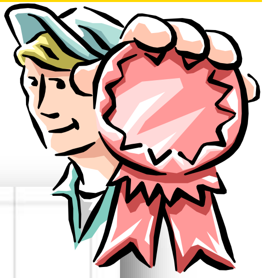


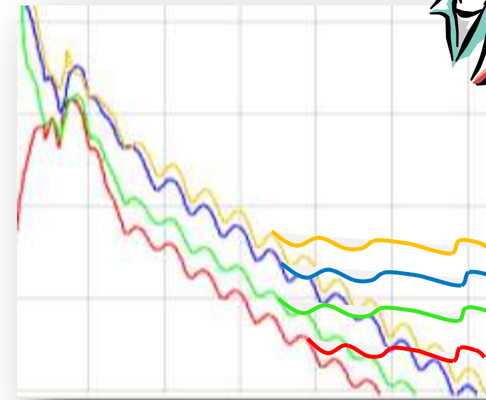




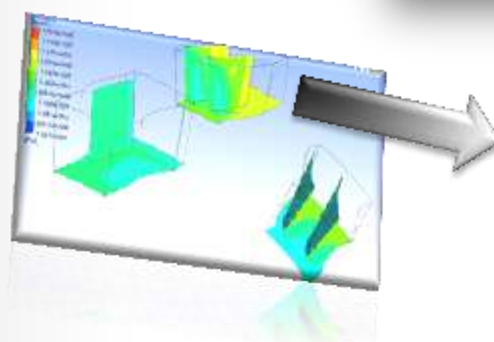
- CoP=64% and 65%
  - small value
  - Numerical error?
  - Model error?
- Important Variables
  - Parameter Reduction
- MoP is plausible

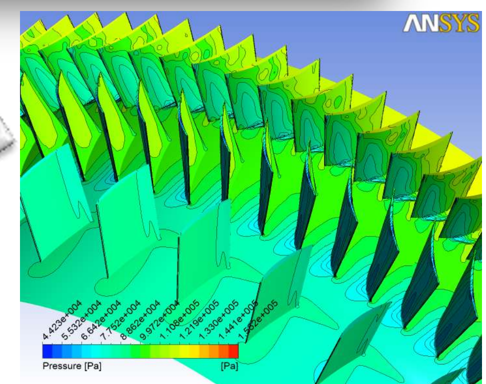
Trouble Shooting for small CoP

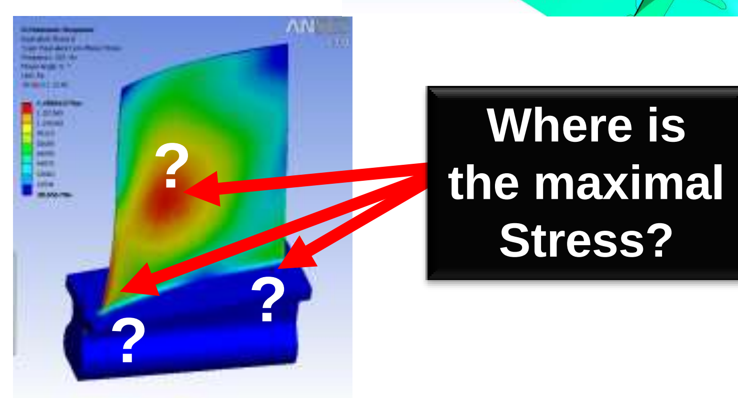




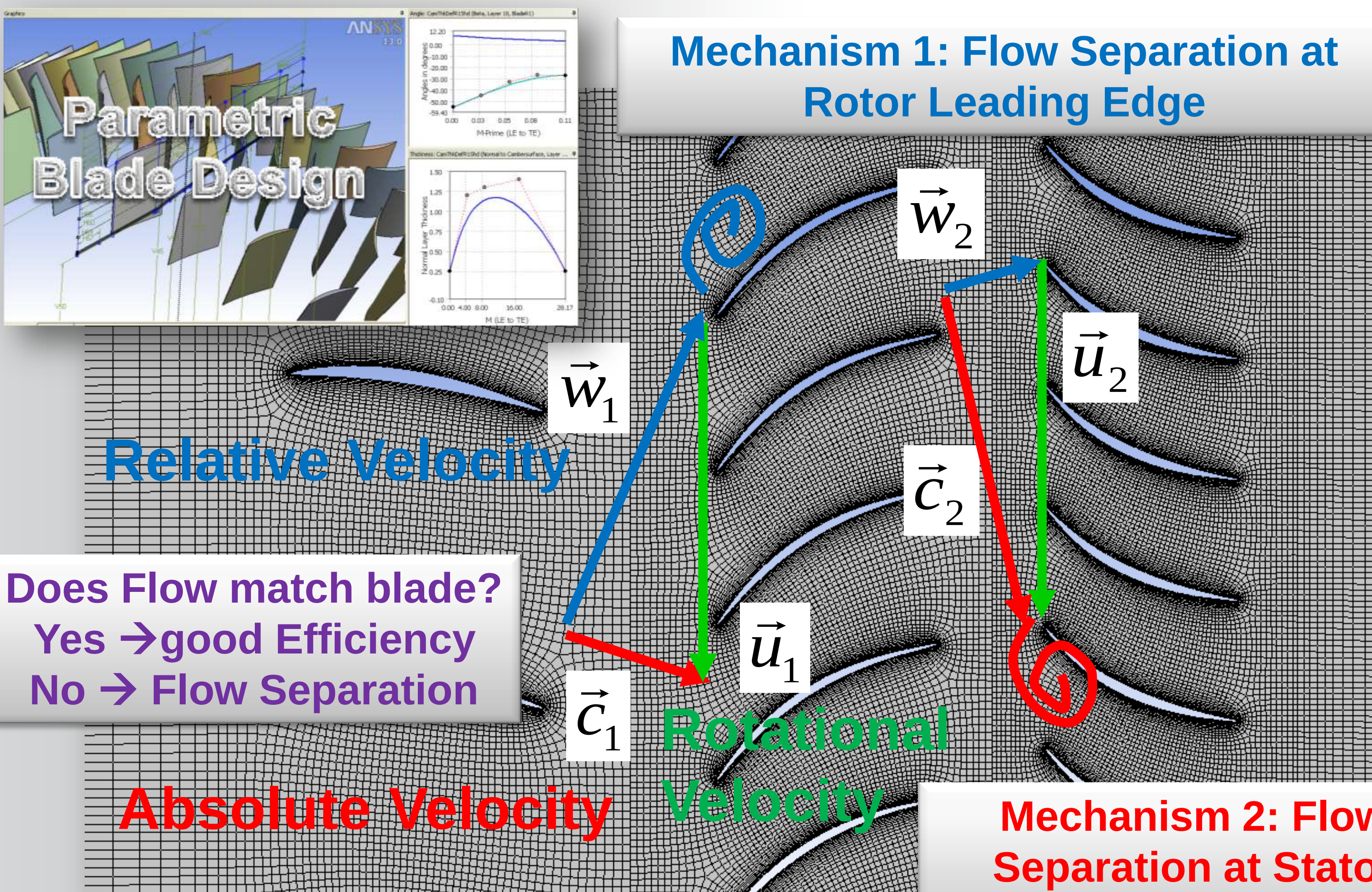
- Number of Evaluated Designs?
  – Check CoP(80)~CoP(150)
- Numerical Error?
  – Best-Practice!
- Model Error?
- Multiple Mechanisms
  – Use alternative Output
- Options:
  – Design Optimization
  – Meta-Model in Subspace







Multiple Mechanism



Mechanism 1: Flow Separation at Rotor Leading Edge

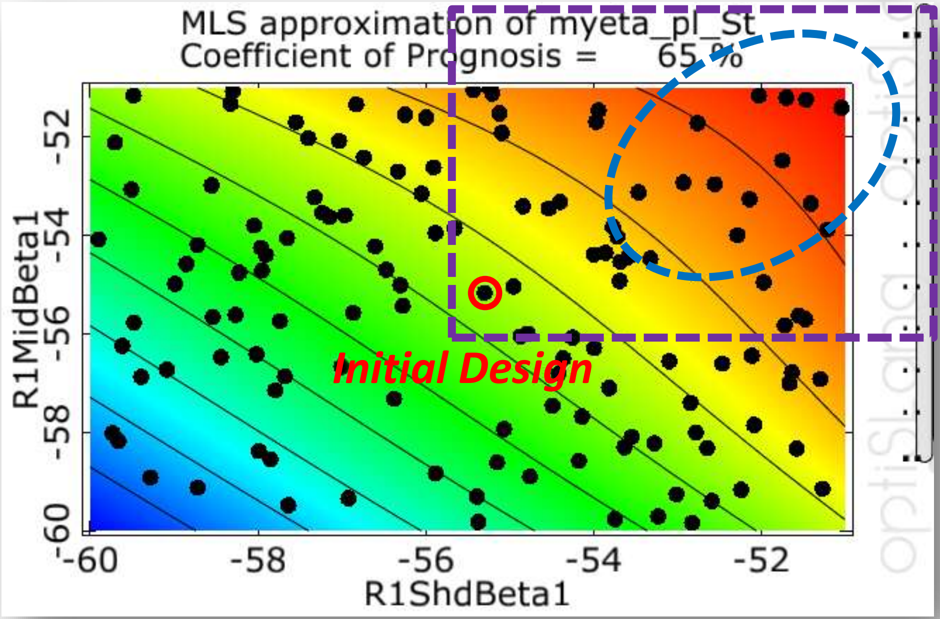
Does Flow match blade?
Yes → good Efficiency
No → Flow Separation

Mechanism 2: Flow Separation at Stator Leading Edge

Design Optimization, Strategy

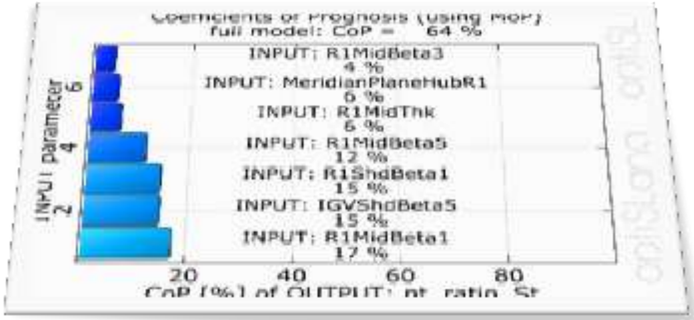
Sensitivity Analysis:

- Shows potential
- Indicates global optimum
- Parameter reduction
- Modify parameter space

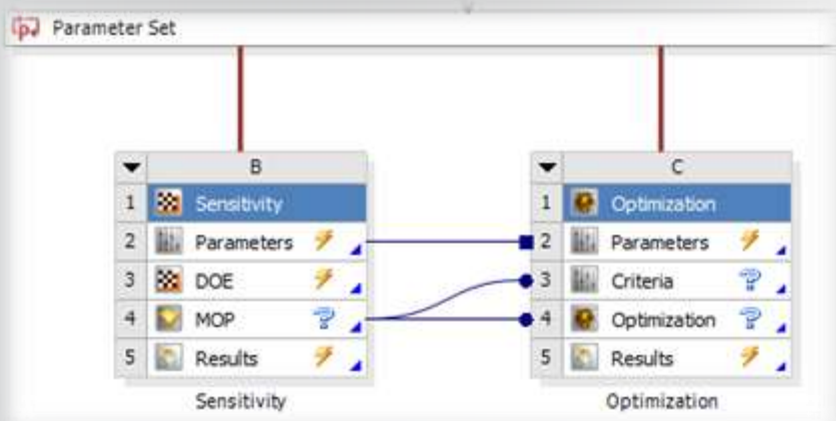


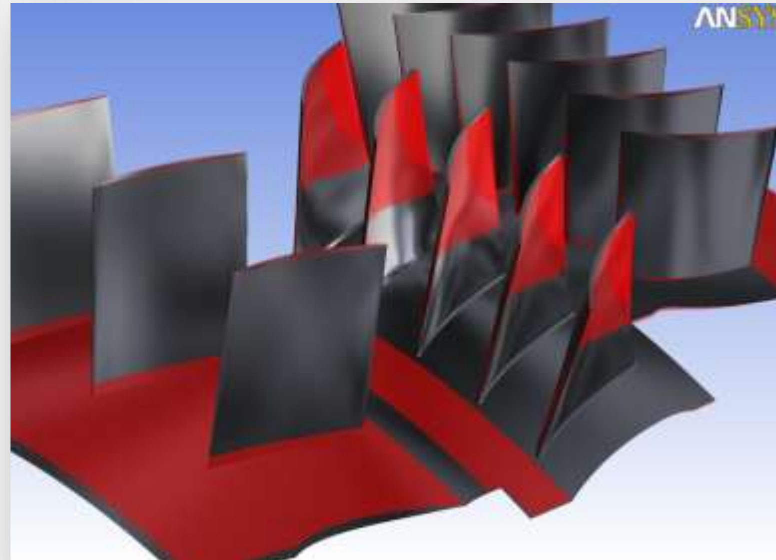
Strategy:

- Get best Design from SA/MoP
- Evaluate this Design and get initial for:
- Optimization in sub space: ARSM
  - Small Number of Parameter
  - Global Optimum



Design Optimization, Summary





	Initial Design	Best Design SA	Best Design Solved (MoP)	Best Design ARSM
Efficiency [%]	87.0	88.0	88.9 (91.0)	88.9
p_{tot} Ratio [-]	1.41	1.41	1.41 (1.44)	1.41
Max. Stress [MPa]	219	235	232 (230)	239
#Designs	1	150	1 (0)	100