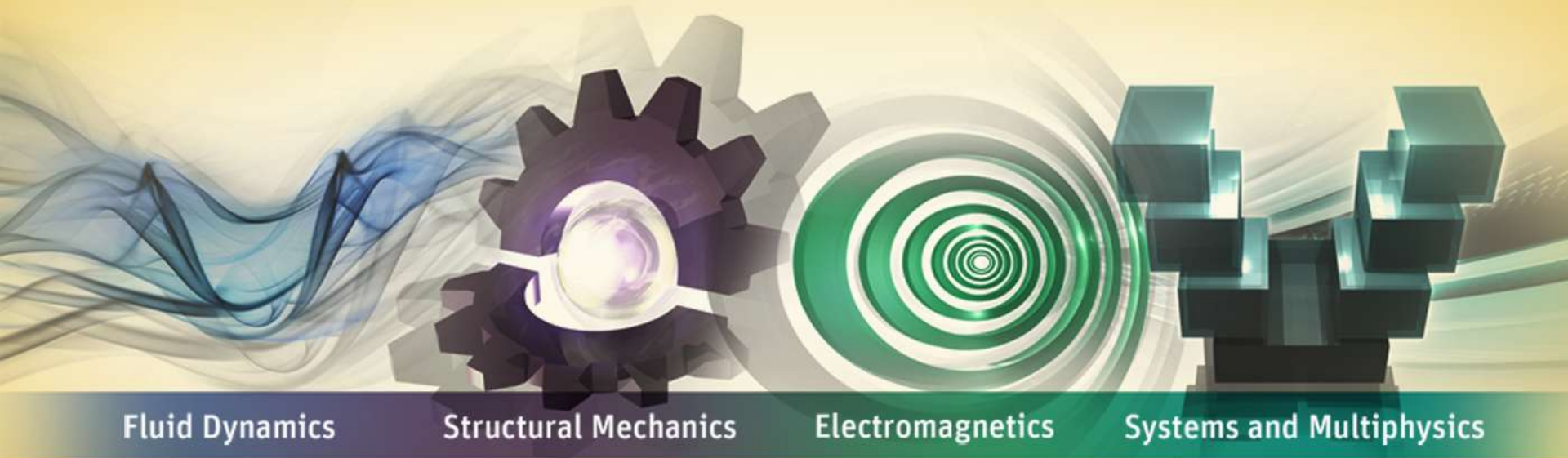


Robust Design Optimization of an Axial Compressor



Fluid Dynamics

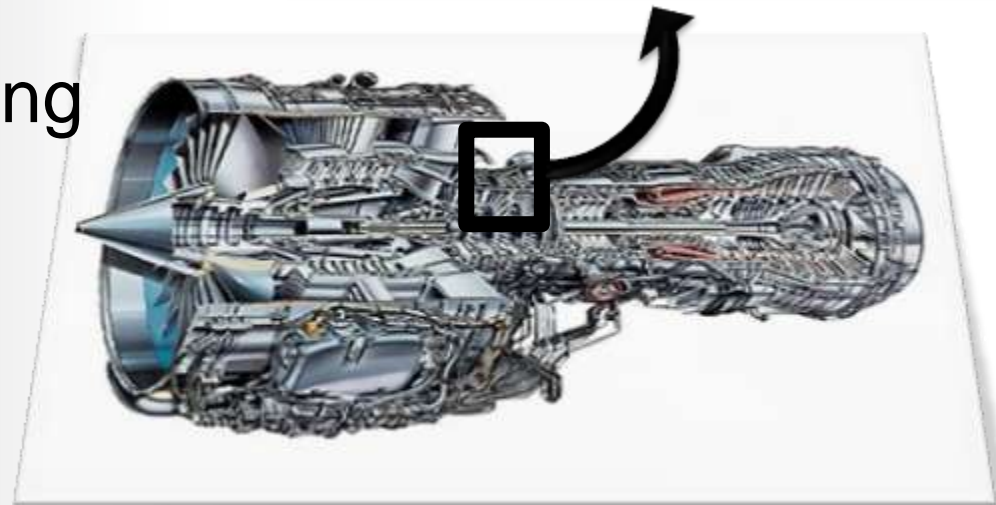
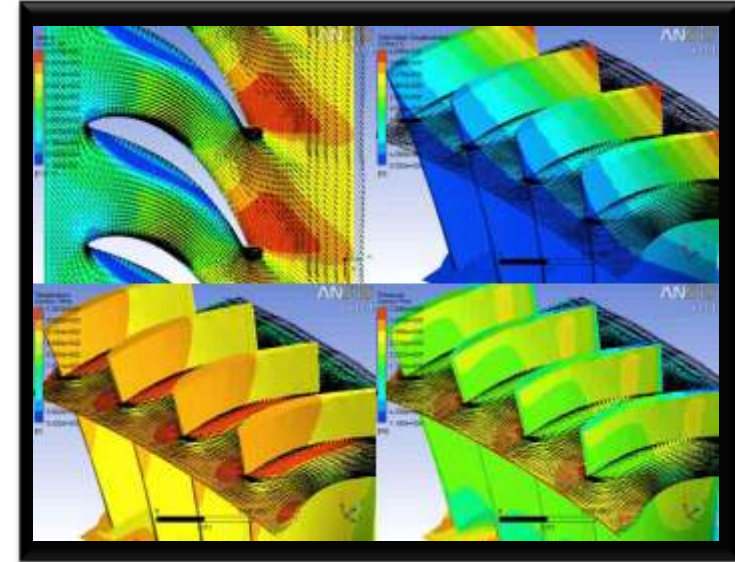
Structural Mechanics

Electromagnetics

Systems and Multiphysics

Johannes Einzinger
ANSYS Germany GmbH

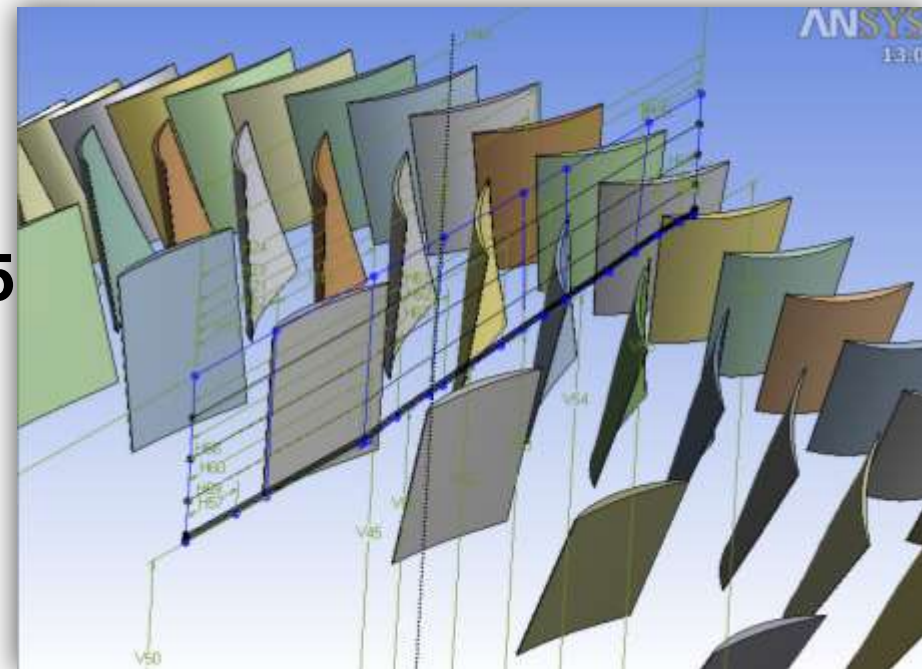
- Turbo Machines show:
 - Rotating and stationary Parts
 - Transient Flow Field
 - Choke, Stall...
 - ...
 - Dynamic Blade Loading
 - ...



**High Requirement
for Optimization**

Primary Design, PCA Engineers

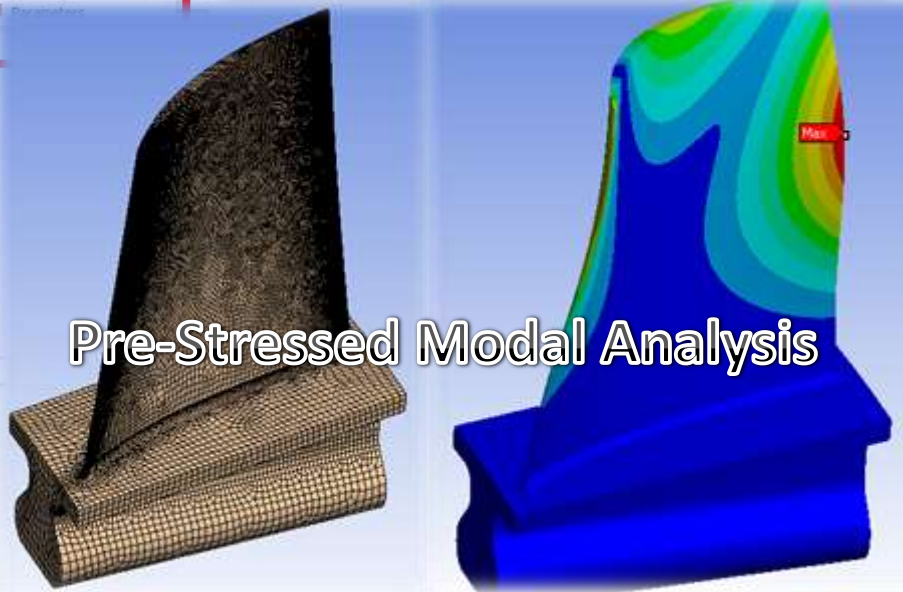
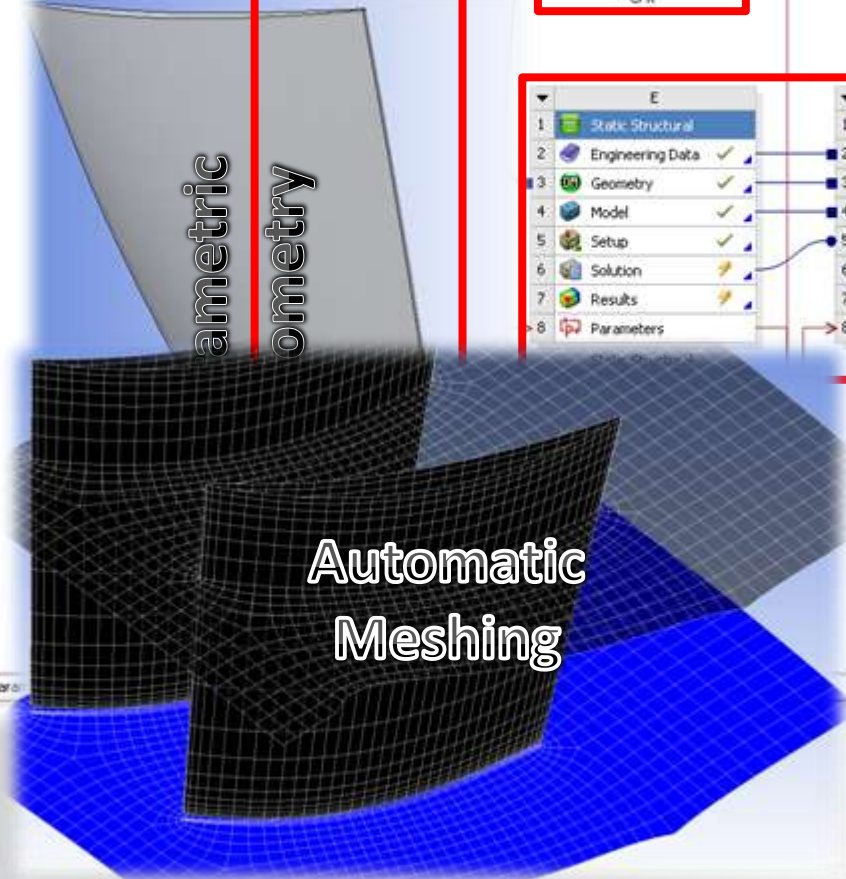
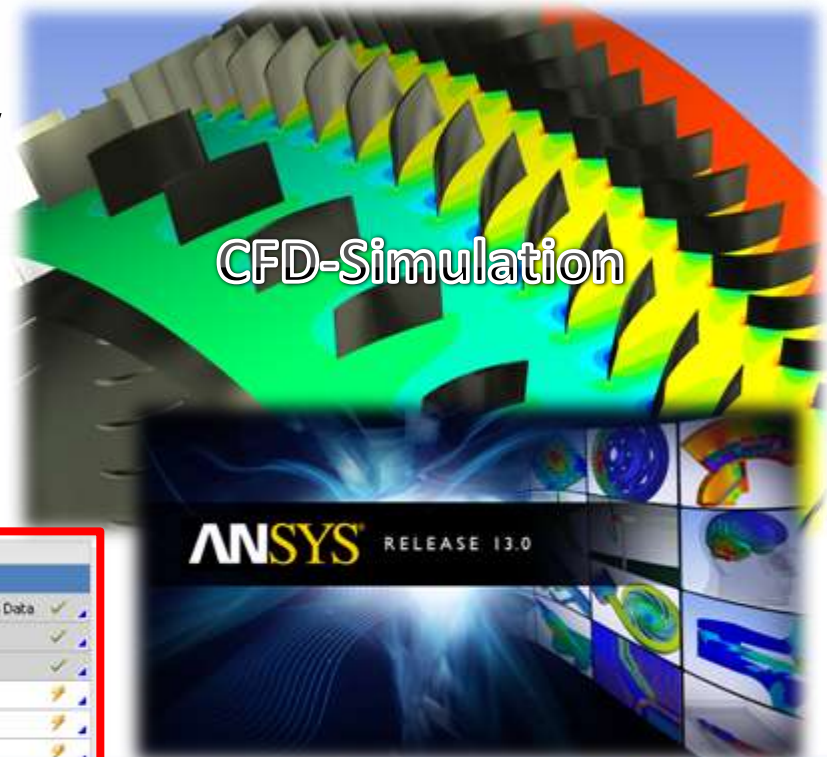
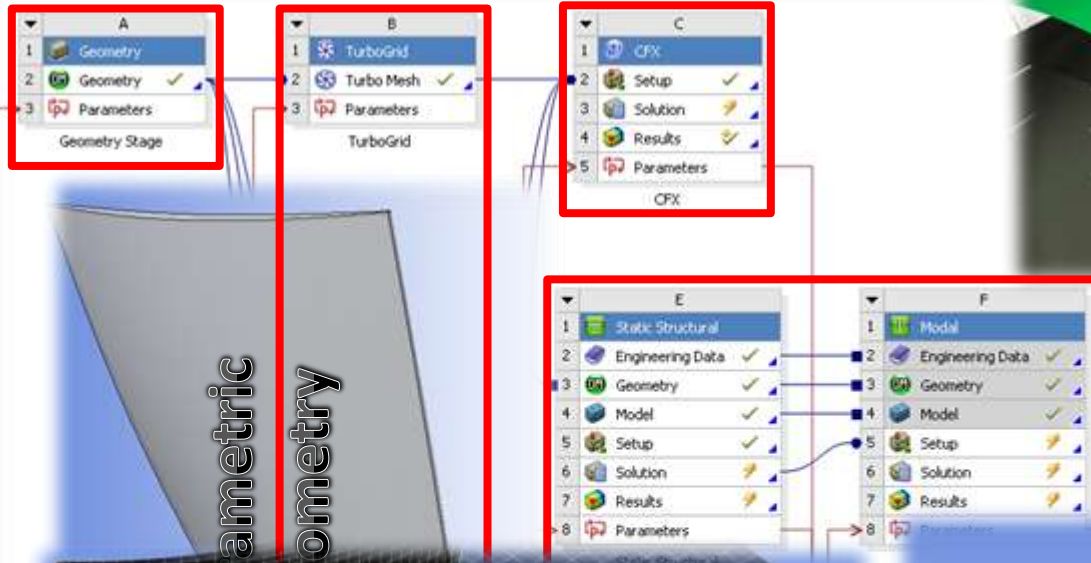
- 1.5 Stage Axial Compressor
- IGV(n=37)
- R1 (n=71, Gap @ Shroud 2% Span)
- S1 (n=91, Gap @ Hub 2% Span)
- Pressure Ratio $\Pi=1.4$
- Mass Flow Rate 10.6 [kg/s]
- Diameter $d = 0.525$ [m]
- Rot. Vel. $\Omega = 9300$ [rpm]
- Blade Mach Number $M_u=0.75$
- Specific Speed $n_s = 1.3$
- Specific Diameter $d_s=2.3$
- Load Coefficient $\Psi=0.45$



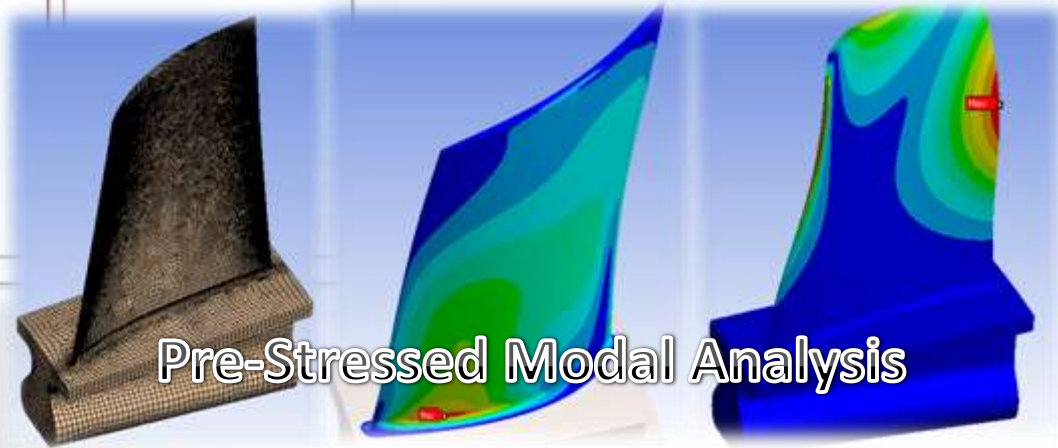
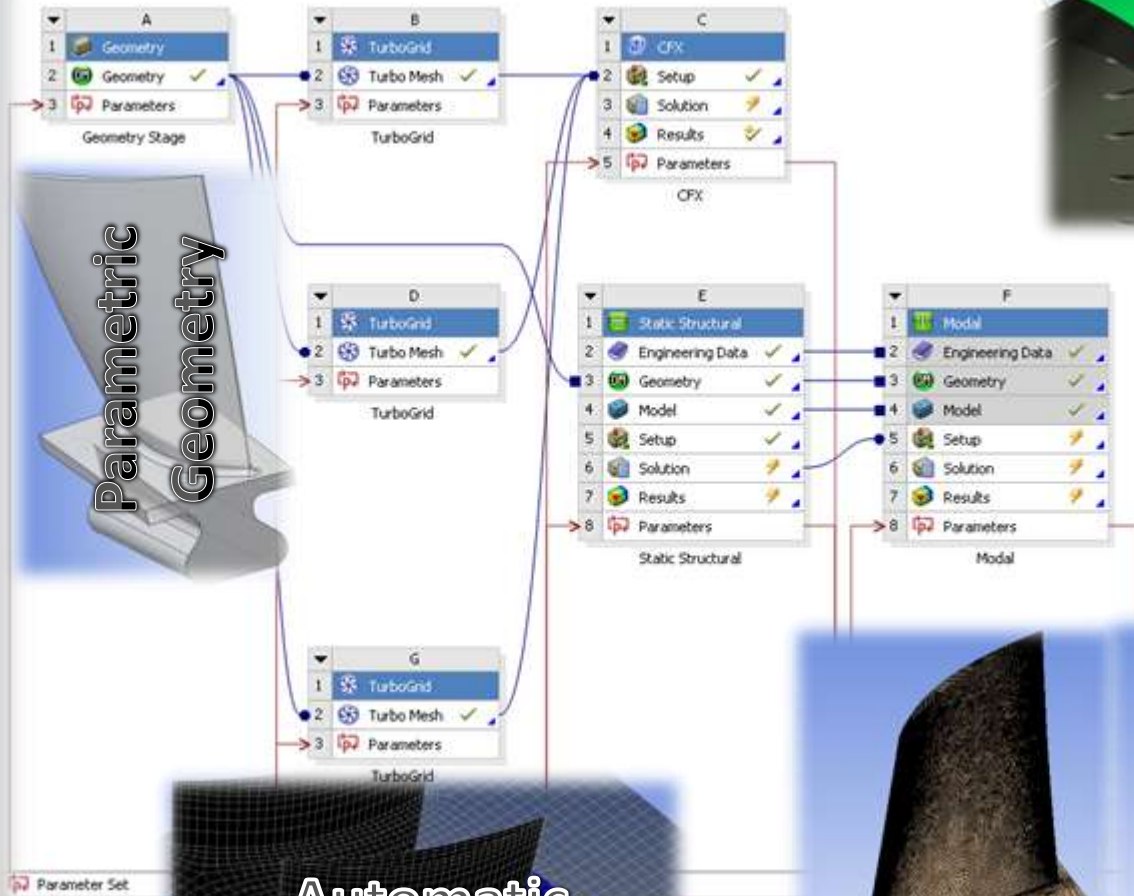
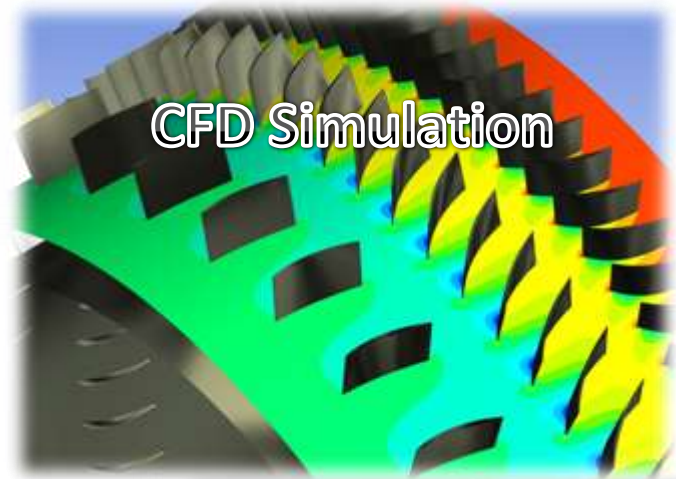
- **Parametric Geometry**
- **Automatic Meshing**
- **Automatic Solution**
 - Fluid Mechanics
 - Structural Dynamics
- **Sensitivity Analysis**
- **Design Optimization**
- **Robustness Evaluation**



Process Overview



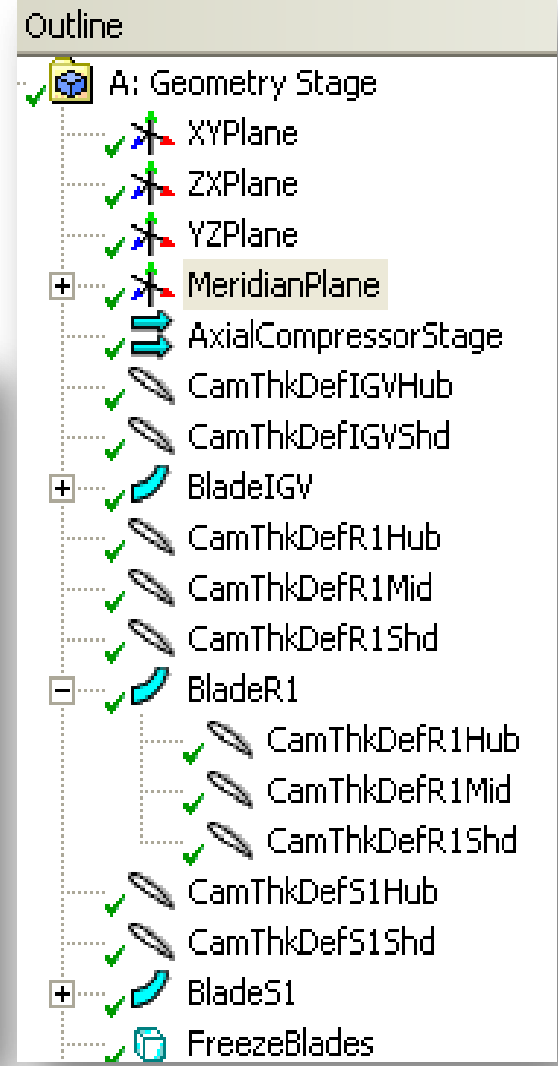
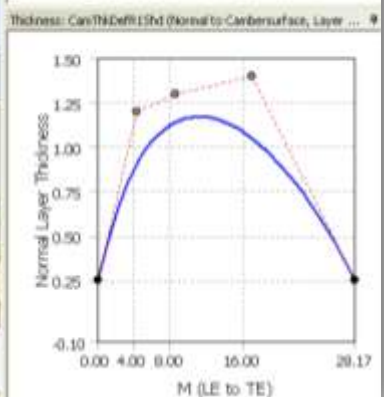
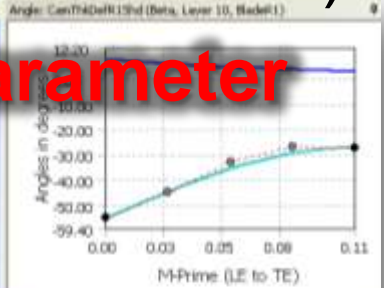
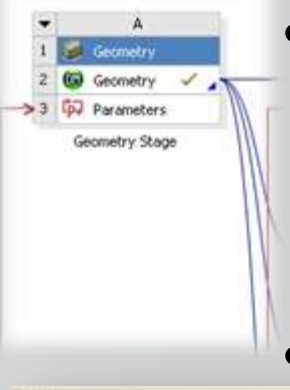
Process Overview



Geometry, Aero Dynamic

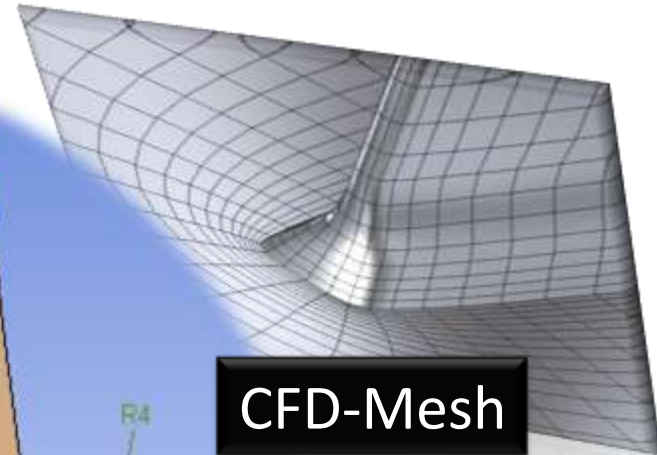
- Camber/Thickness for
 - IGV, R1, S1; 2-3 Layers
 - 5 β_i per Layer, 3xThk
- Hub, 8 radii (const. Shroud)

47 CAD Input Parameter

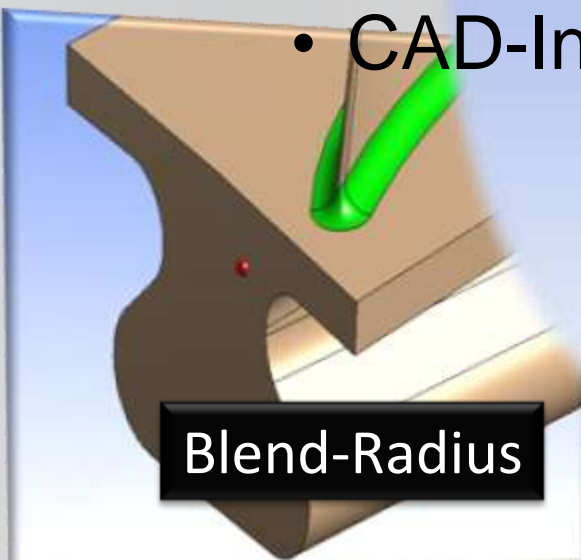


Geometry, Blade Design

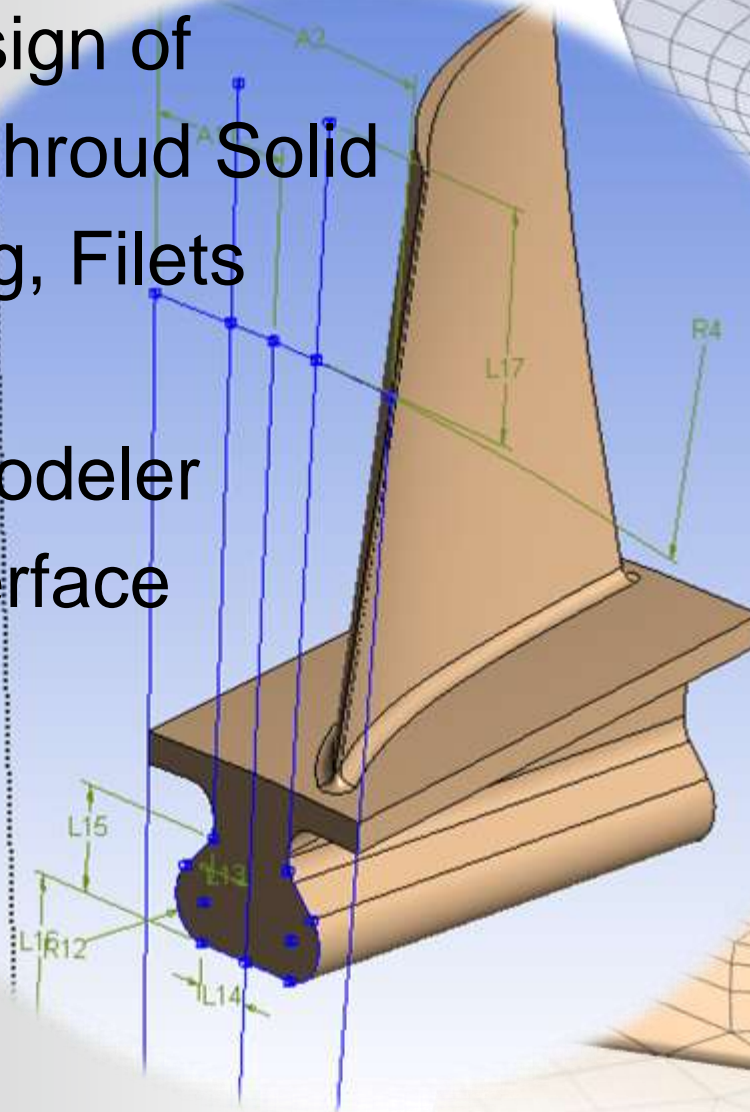
- CAD Design of
 - Hub/Shroud Solid
 - Casing, Filets
 - ...
- DesignModeler
- CAD-Interface



CFD-Mesh



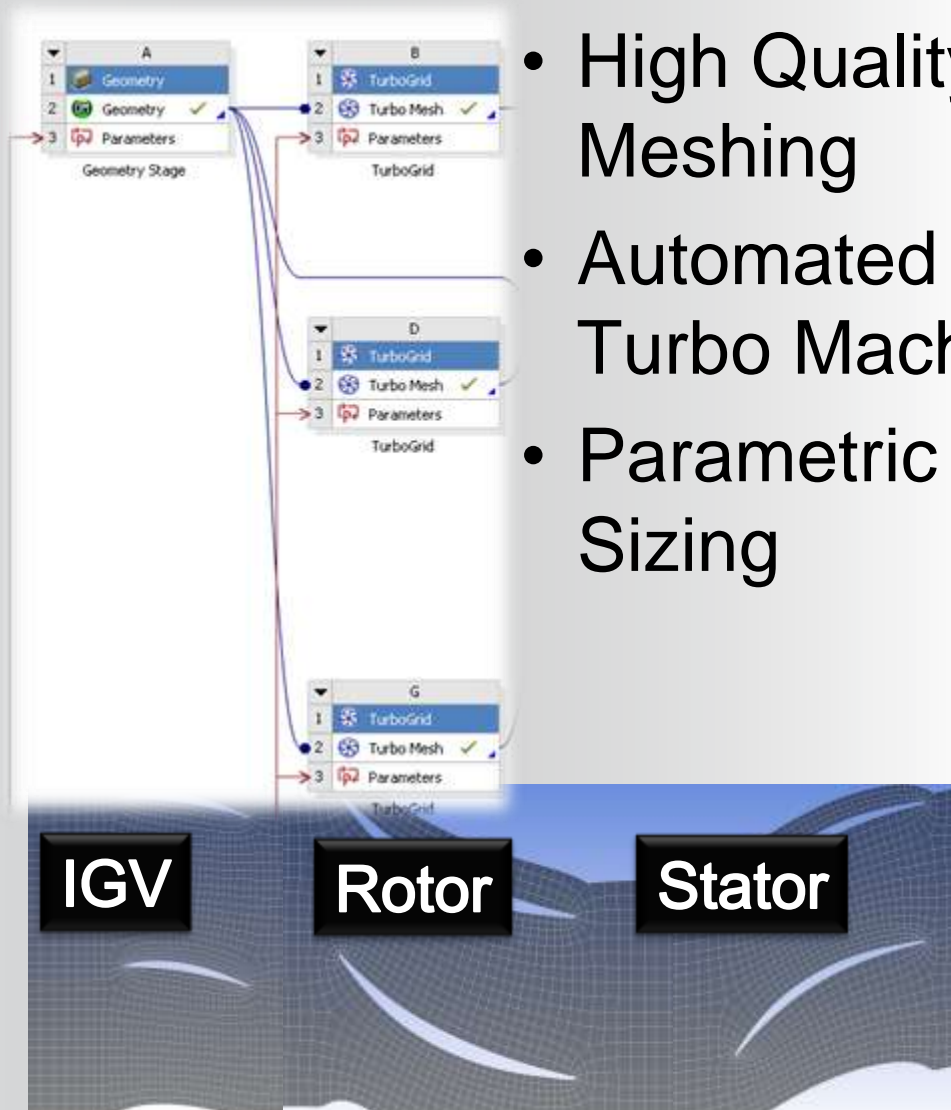
Blend-Radius



FEM-Mesh

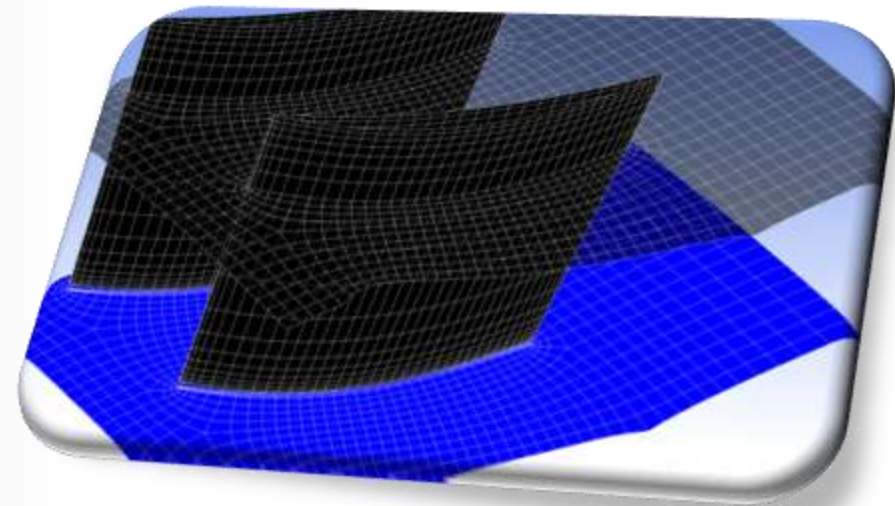
Meshing, TurboGrid

- High Quality Meshing
- Automated for Turbo Machinery
- Parametric Mesh Sizing

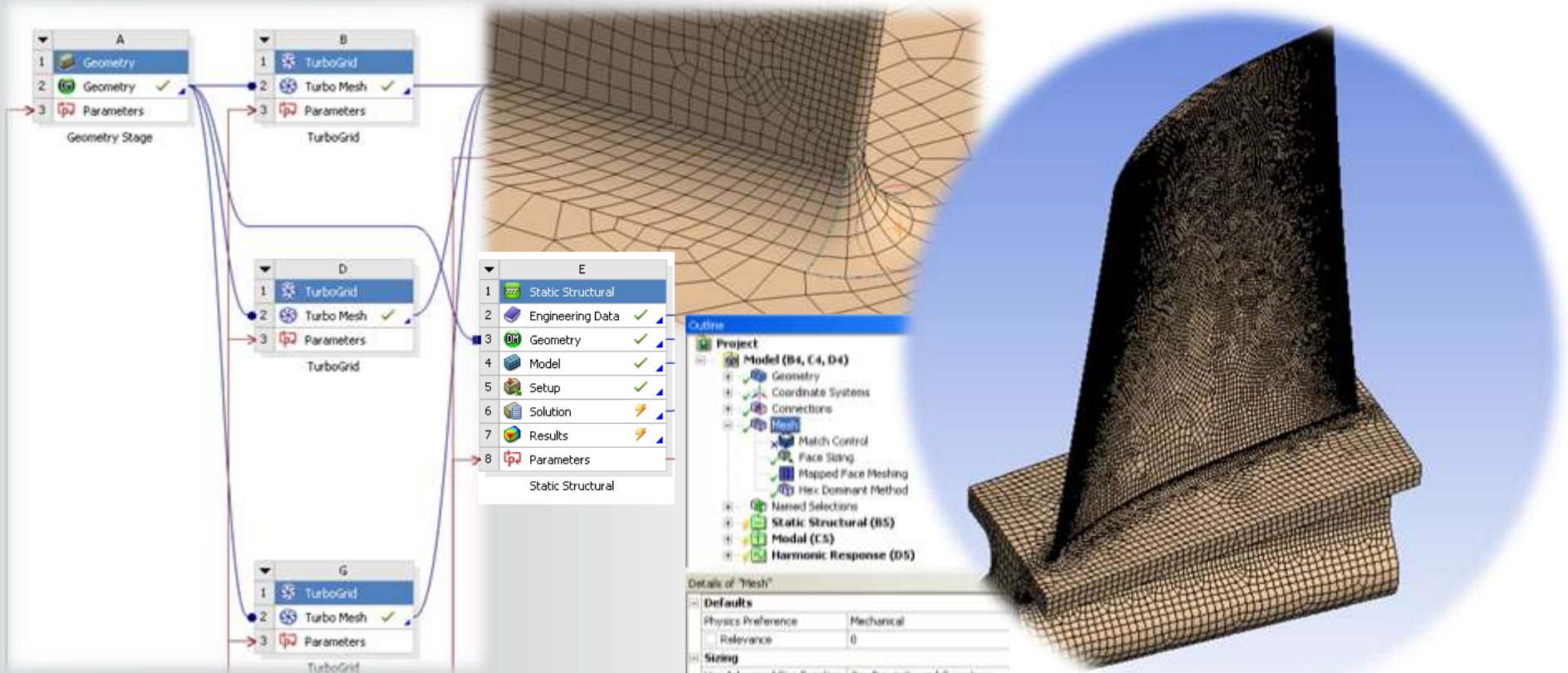


The Expression Editor window displays a table of parameters and their values. The table has four columns: ID, Parameter Name, Value, and Unit. The parameters are listed in the table below:

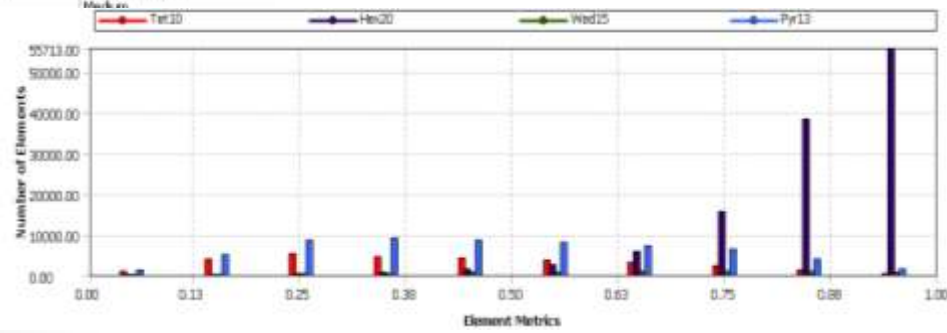
ID	Parameter Name	Value	Unit
1	MeshSizeFactor	1	
2	MinMeshAngle	minVal(Minimum Face Angle)@Outlet	



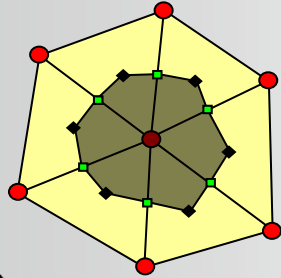
Meshing, General



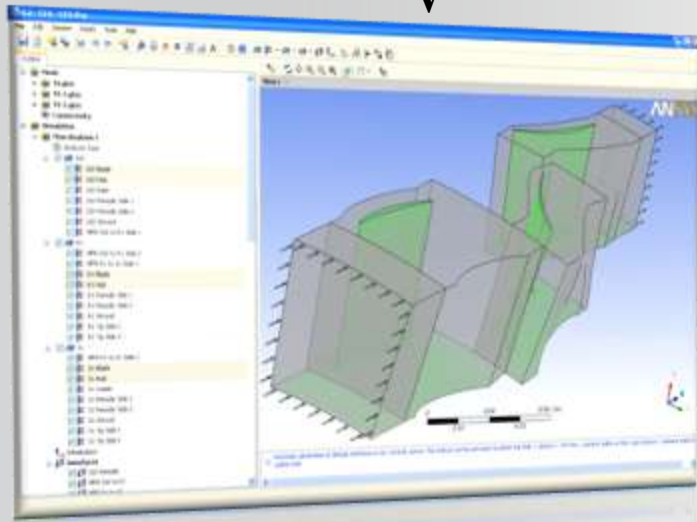
- Hex-Dominant
- Automatic Size Functions
- ...



CFD Simulation



$$\frac{\partial}{\partial t} \int_V \rho \phi dV + \oint_A \rho \phi \mathbf{V} \cdot d\mathbf{A} = \oint_A \Gamma \nabla \phi \cdot d\mathbf{A} + \int_V S_\phi dV$$



- **CFD Solver: CFX**
- **Nodal based FVM**
- **Coupled Solution + AMG**
 - Mass & Momentum, Energy...
- **Turbulence Model:**
 - Shear Stress Transport
- **One sector by passage, MFR:**
 - Profile Transformation
 - Periodic Interface

Transient Blade Row Method

Profile Transformation

**Mixing Plane
Frozen Rotor**

Time Transformation

Time Inclining

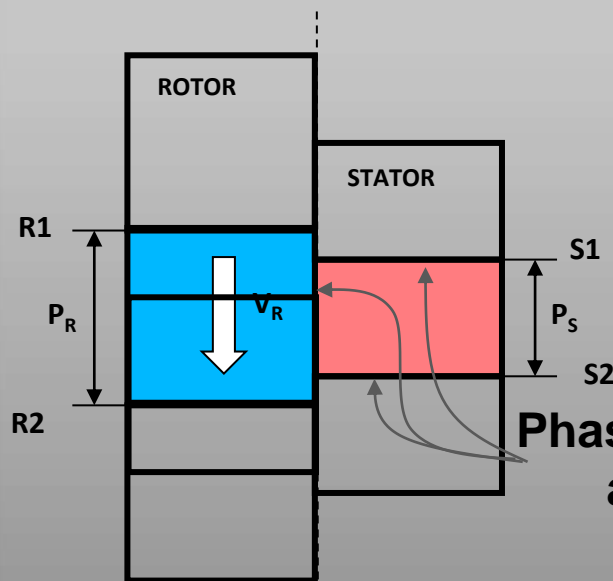
Fourier Transformation

**Shape Correction
Phase Shift**

Harmonic Transformation

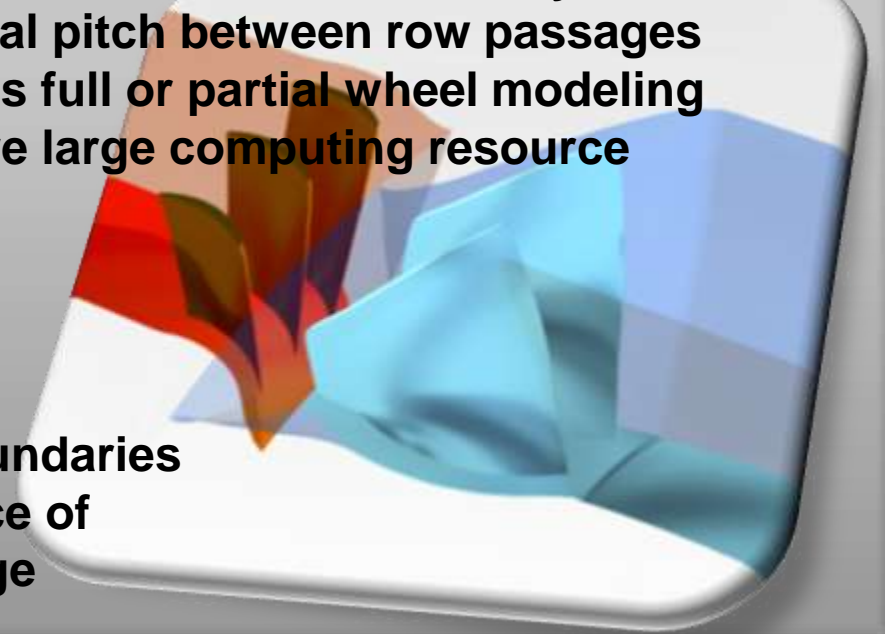
$f(t) \rightarrow F(\Omega)$
R&D

unequal pitch



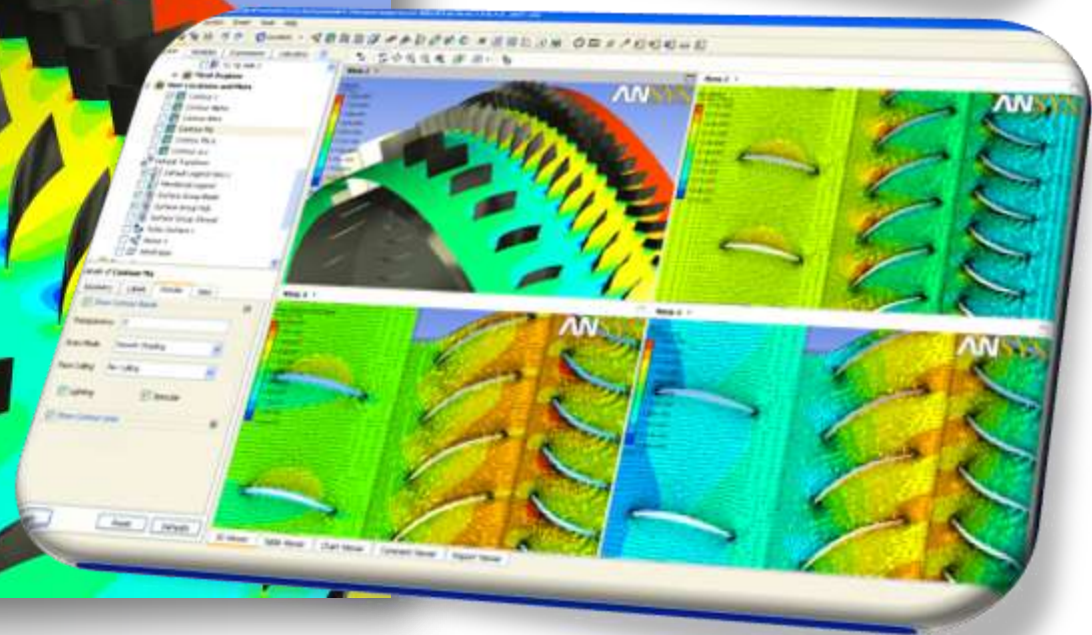
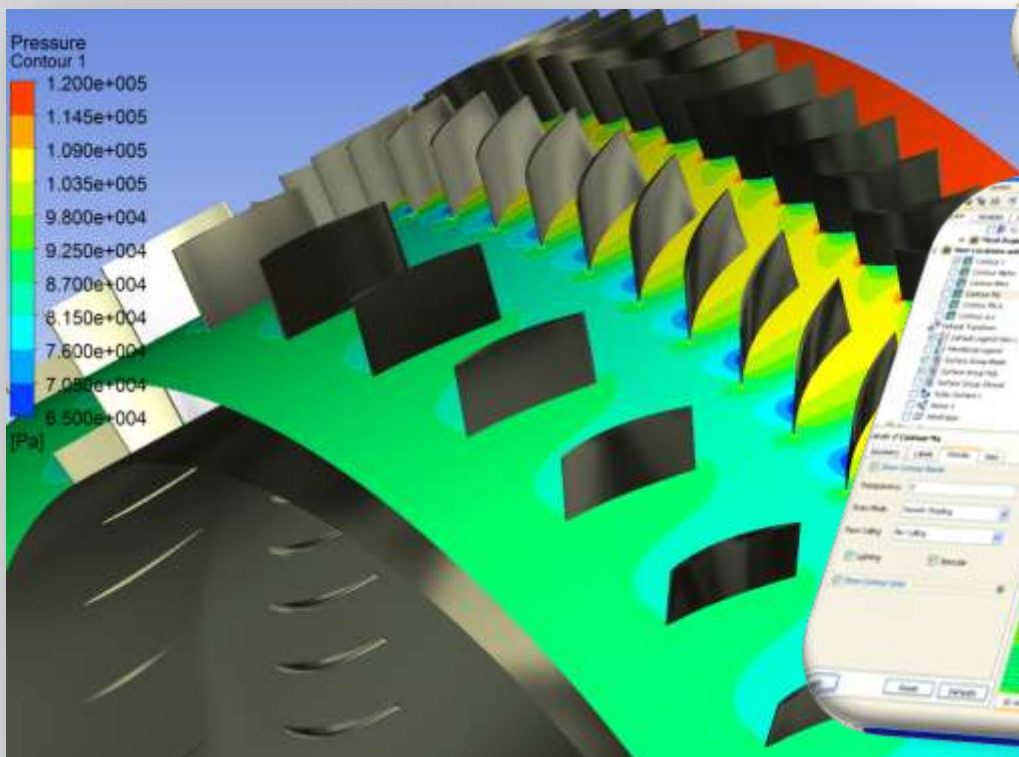
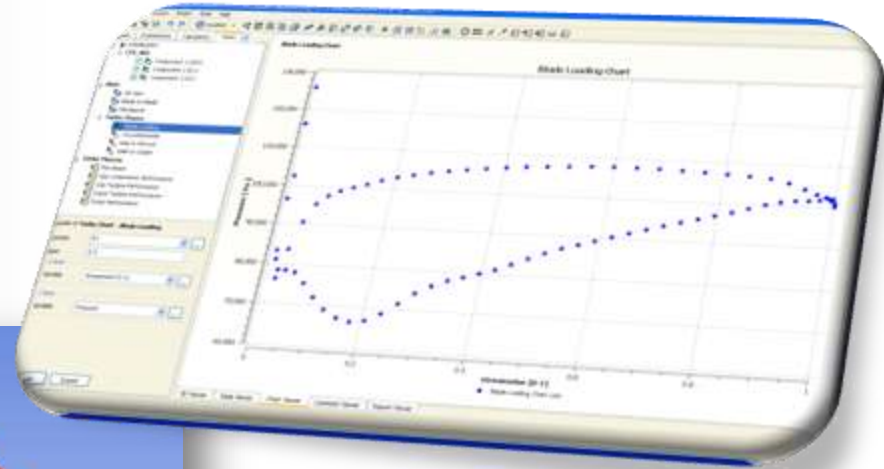
**Phase-shifted boundaries
a consequence of
pitch change**

- Accurate accounts for unsteady interactions
- Unequal pitch between row passages dictates full or partial wheel modeling
- Require large computing resource

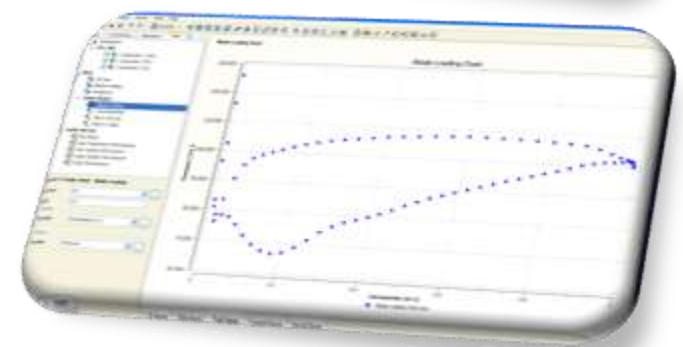
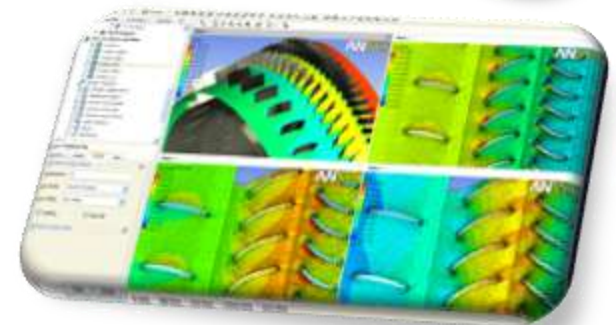
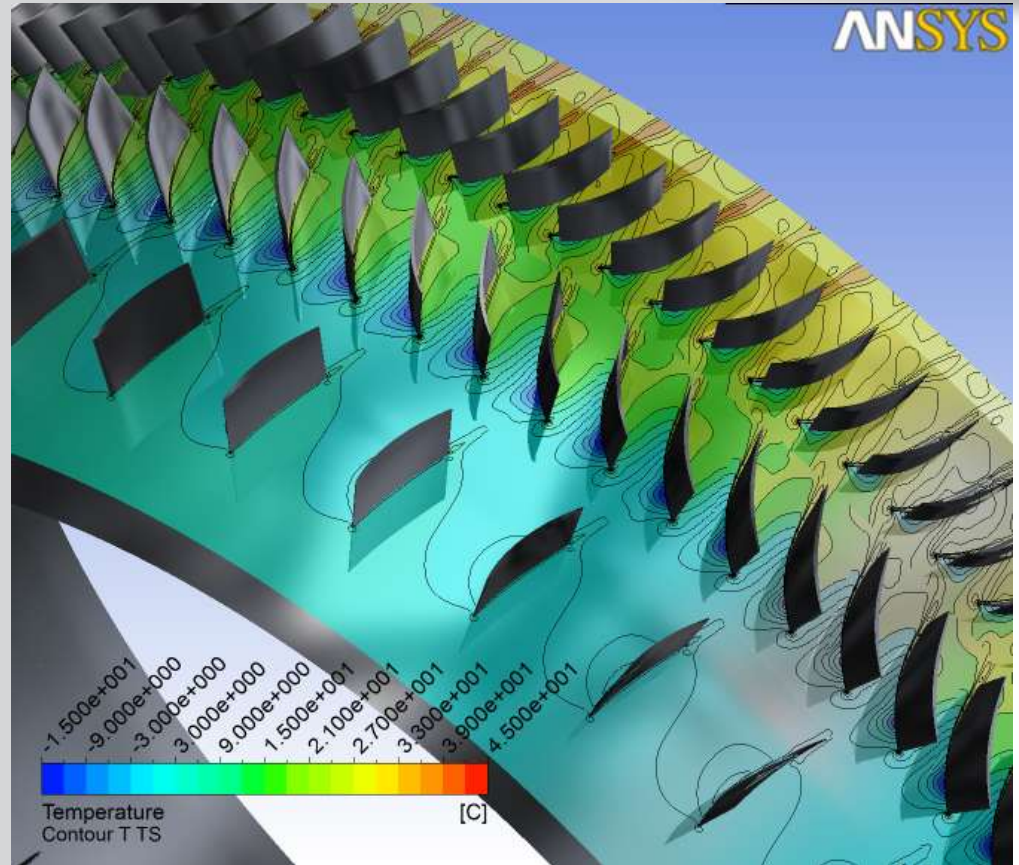
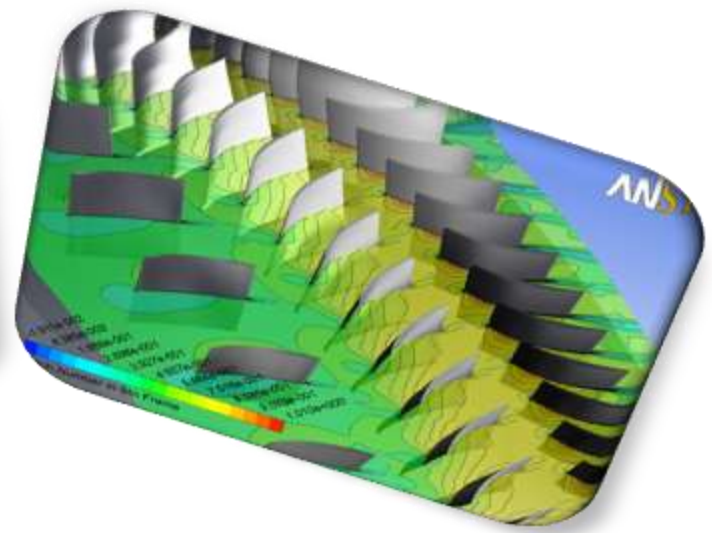
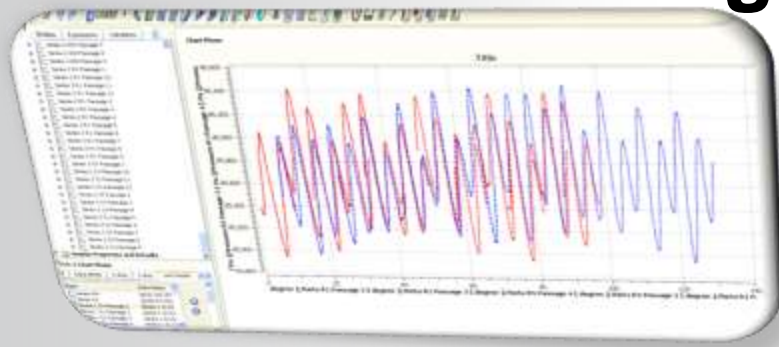


CFD Post-Processing

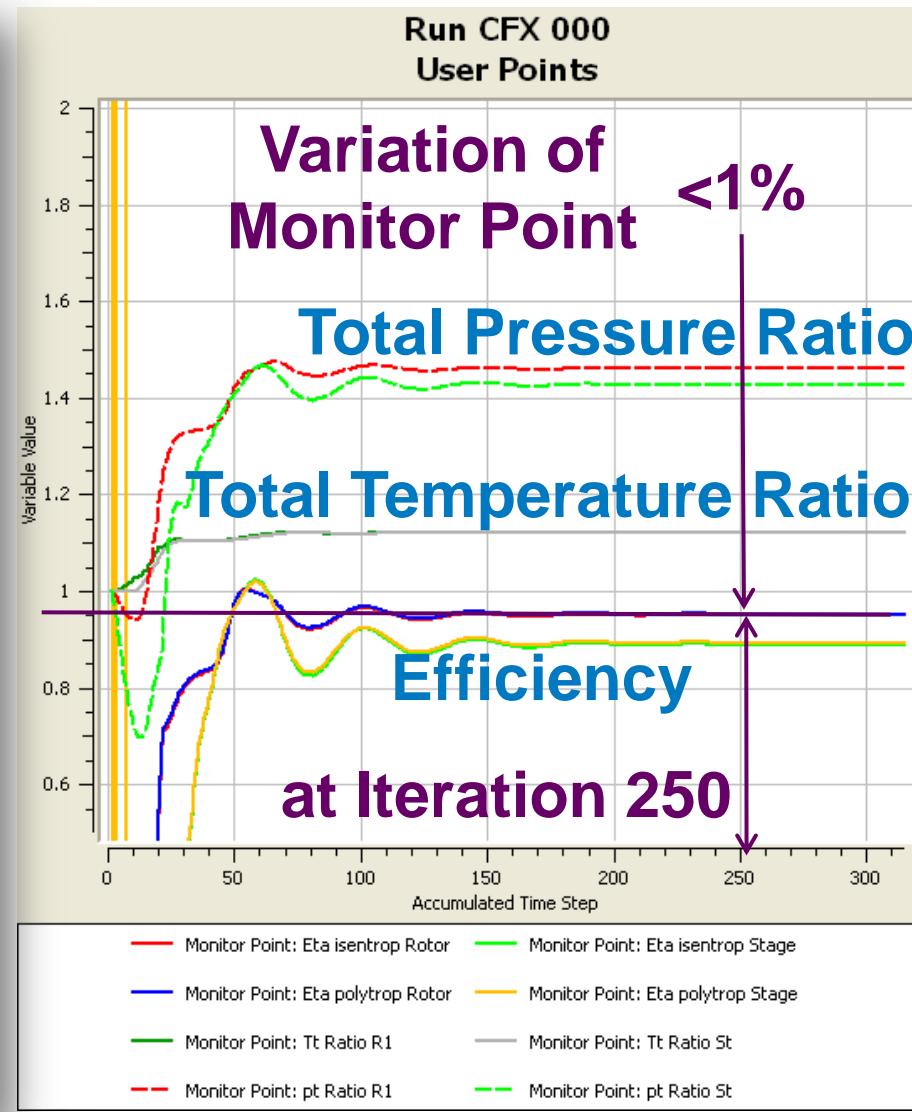
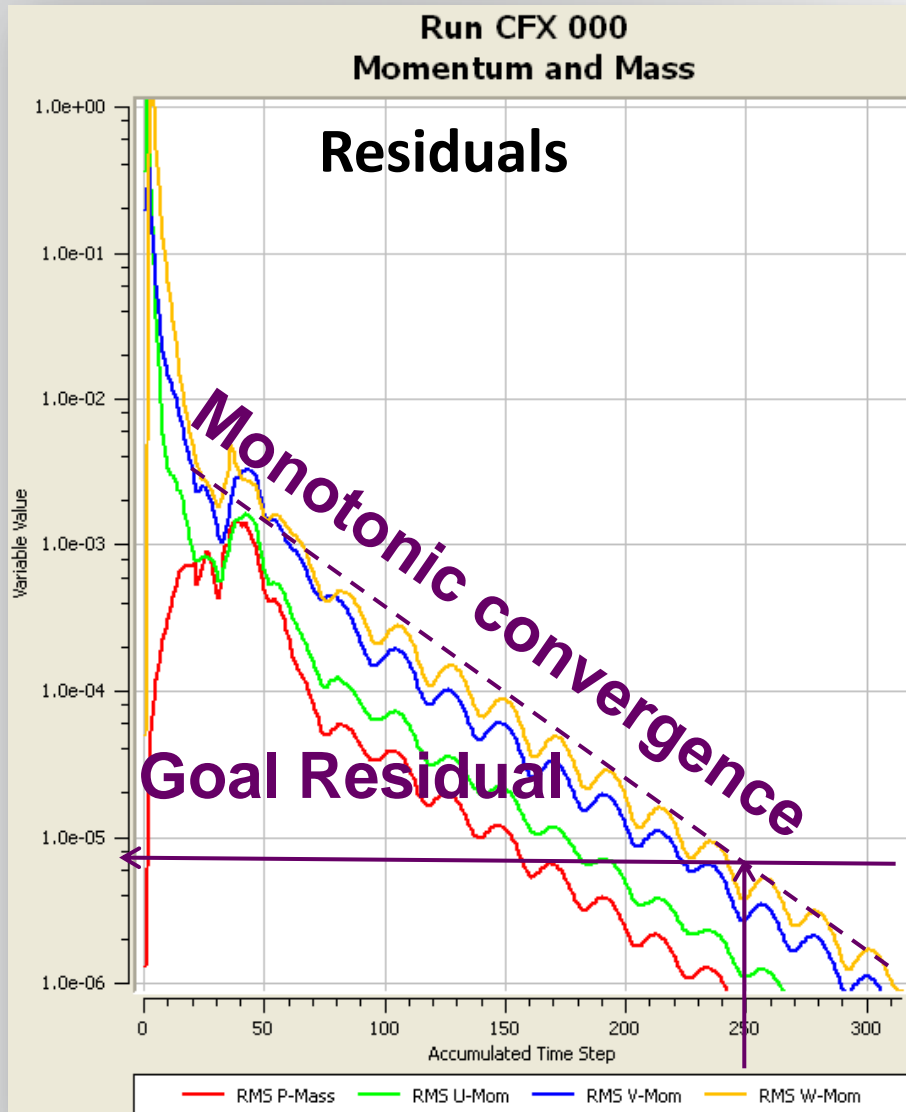
- General Post-Processor
- Turbo Mode
- Highly Automated
- Customizable



CFD Post-Processing

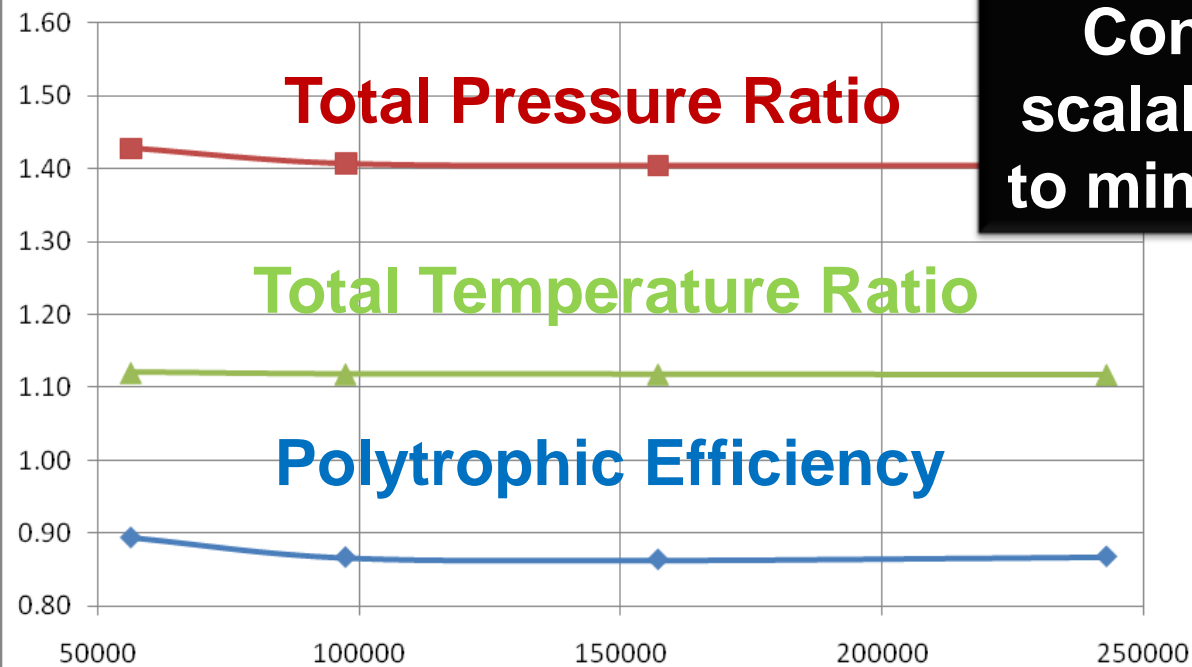


Quality Assurance Iteration Error

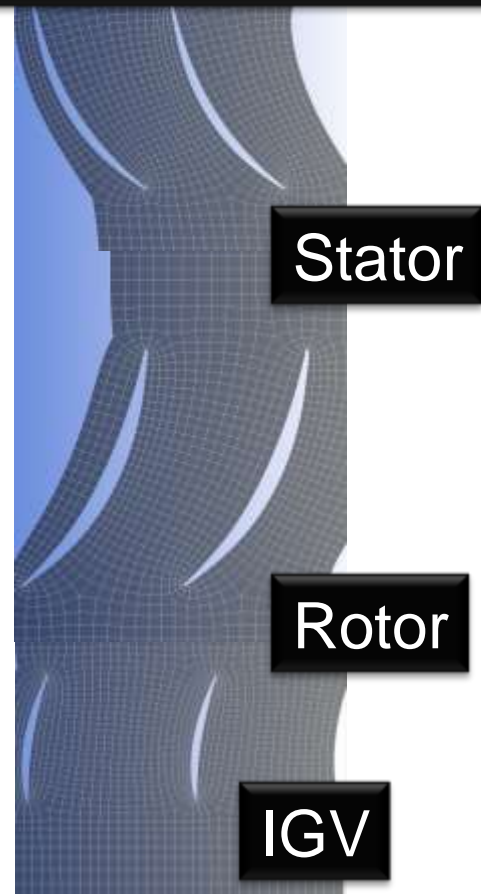


Quality Assurance Discretization Error

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



- **Mechanical Equation System**

$$M \cdot \ddot{u} + D \cdot \dot{u} + K(u) \cdot u = f_0 + f(t)$$

- Linearization

- Decomposition $u(t) = u_0 + \Delta u(t)$

- **Static System (Pre-Stress)**

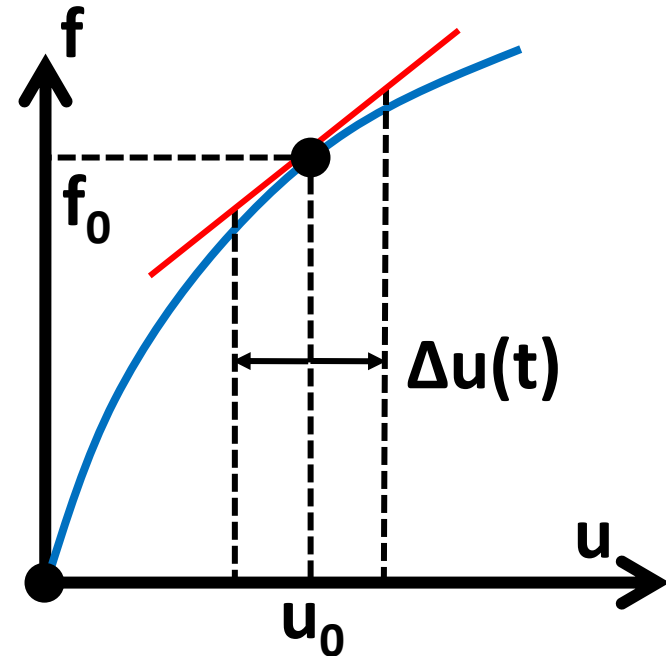
$$K(u_0) \cdot u_0 = f_0$$

- **Modal Analysis**

$$-\omega^2 \cdot M + K(u_0) \cdot \Phi = 0$$

- **Linear dynamic System**

$$M \cdot \Delta \ddot{u} + D \cdot \Delta \dot{u} + K(u_0) \cdot \Delta u = f(t)$$

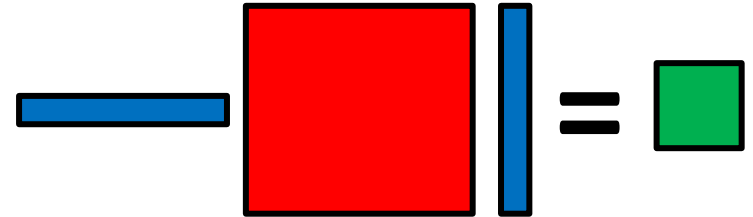


Model Order Reduction

$$M \cdot \Delta \ddot{u} + D \cdot \Delta \dot{u} + K(u_0) \cdot \Delta u = f(t)$$

- Approximation

$$\Delta u(t) = \Phi \cdot q(t)$$



- leads to reduced dynamic System

$$\Phi^T M \Phi \cdot \ddot{q} + \Phi^T D \Phi \cdot \dot{q} + \Phi^T K \Phi(u_0) \cdot q = \Phi^T f(t)$$

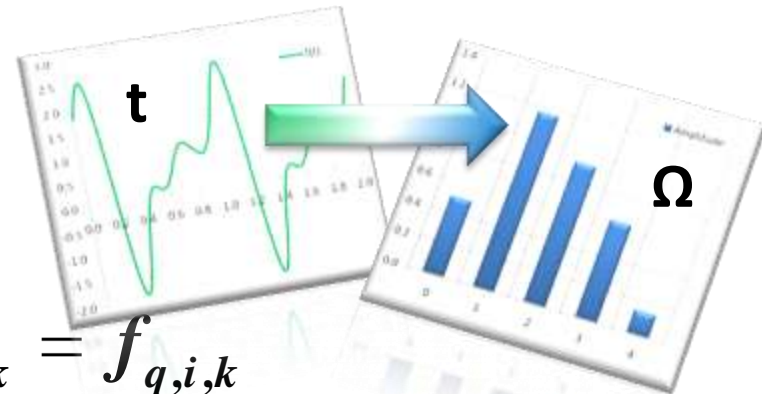
- orthogonality of Φ leads to

$$\ddot{q}_i + 2 \cdot \xi \cdot \omega_0 \cdot \dot{q}_i + \omega_0^2 \cdot q_i = f_{q,i}(t)$$

- Fourier Transformation

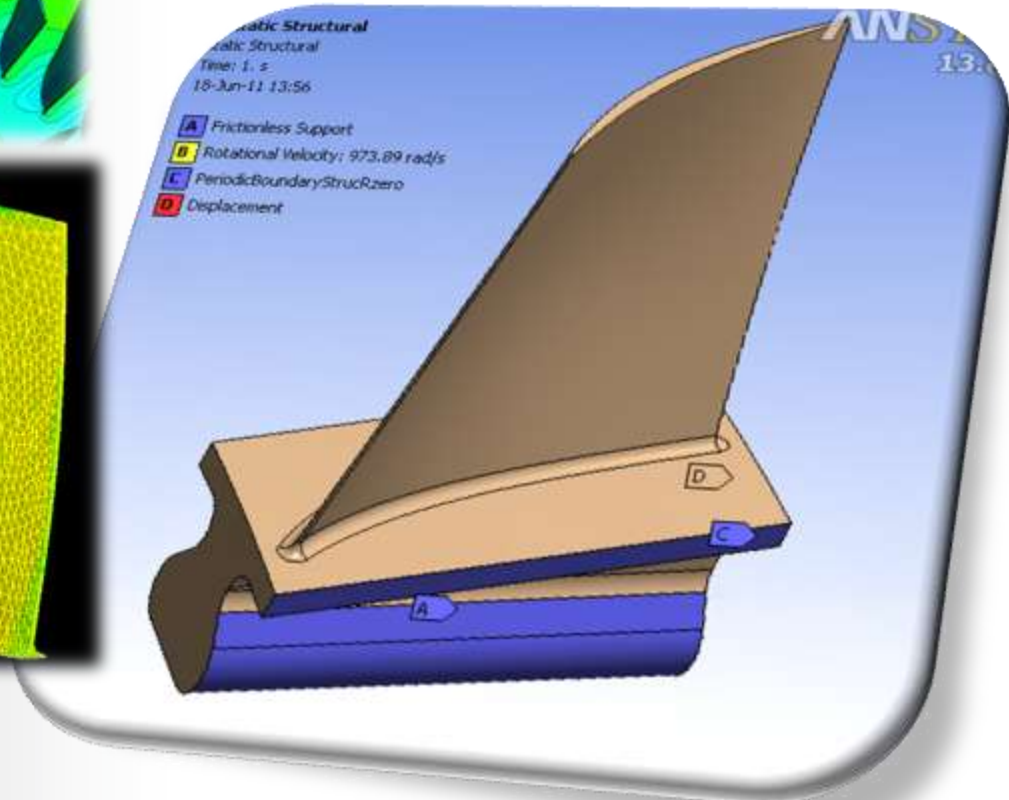
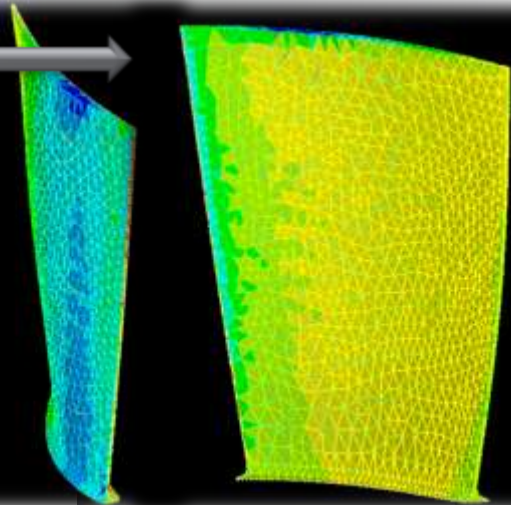
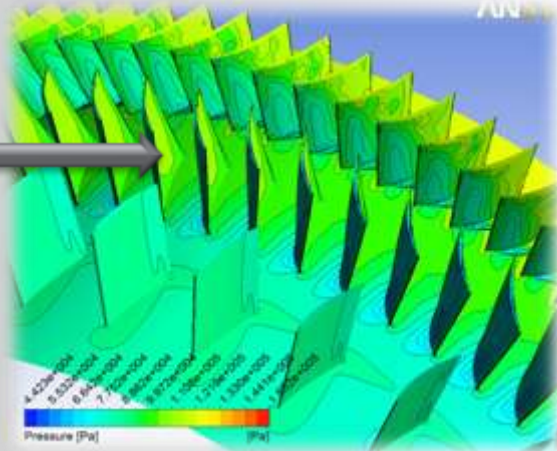
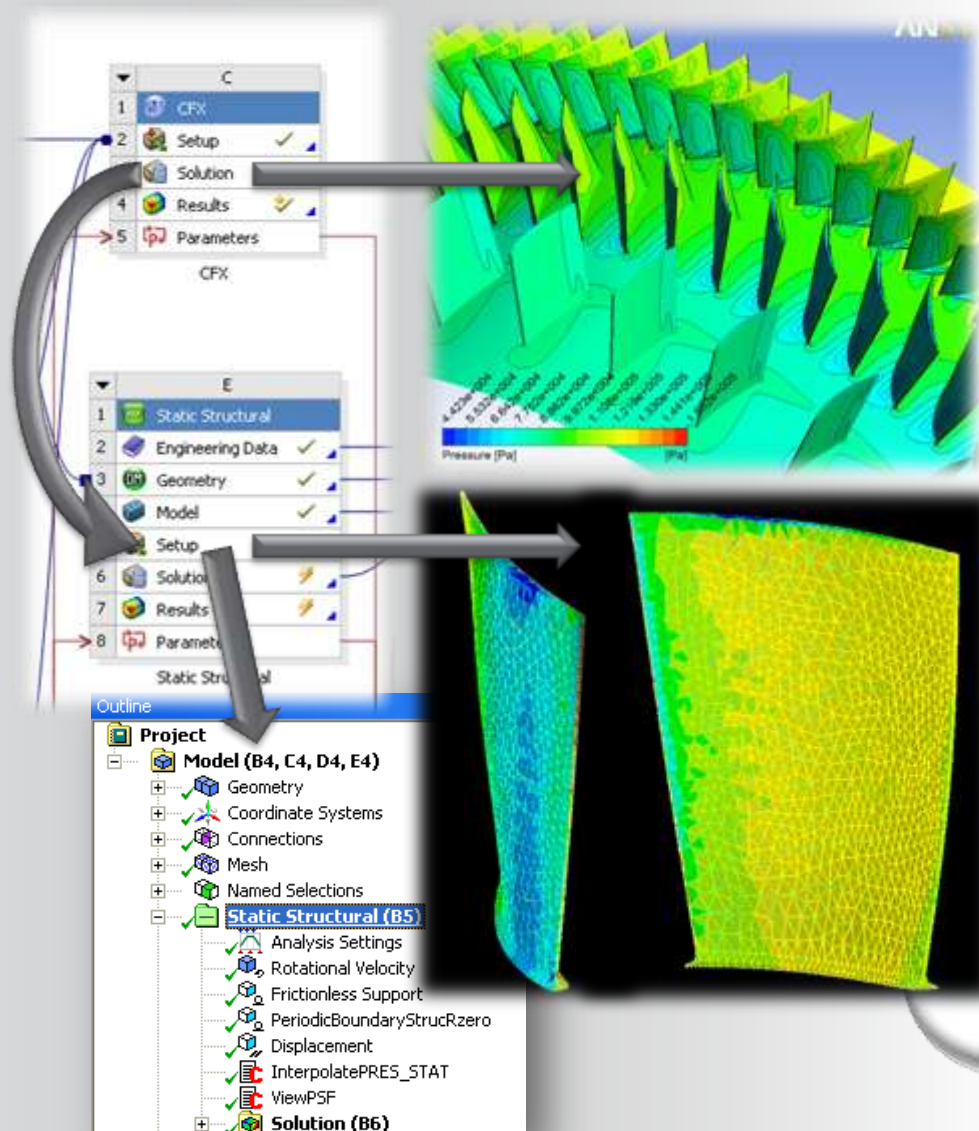
- Time to Frequency Domain

$$\omega_0^2 - \Omega_k^2 + 2 \cdot \zeta \cdot \omega_0 \cdot \Omega_k \cdot j \cdot q_{i,k} = f_{q,i,k}$$



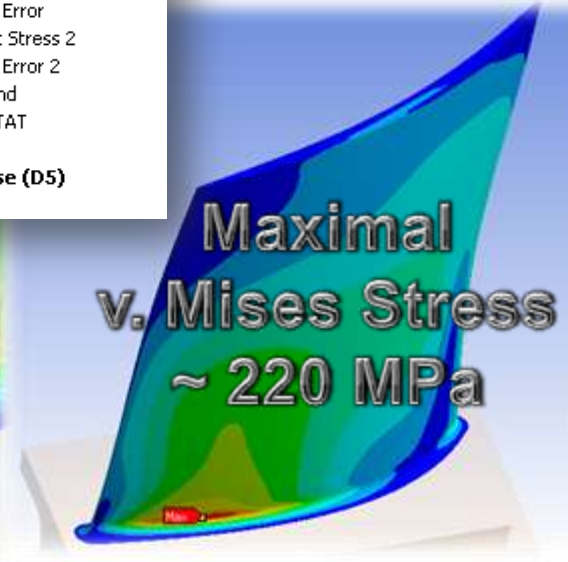
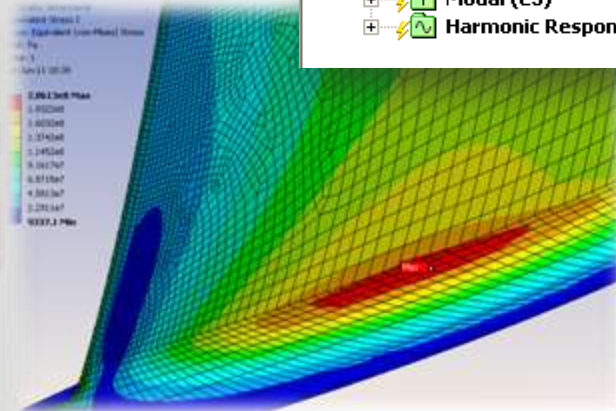
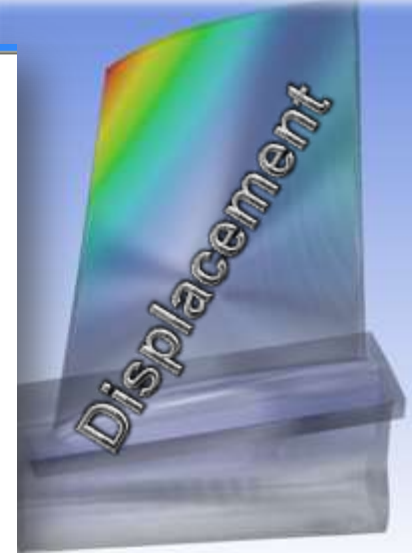
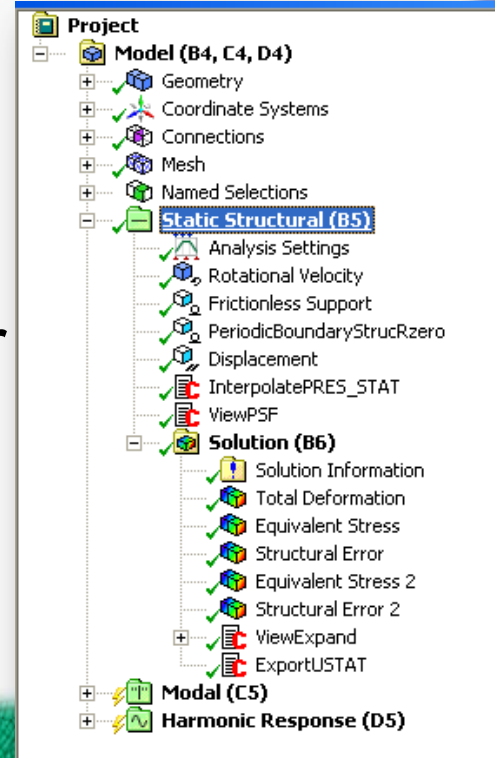
Fluid-Structure Coupling

- Displacements
- Rot. Velocity
- CFD-Pressure



Static Structural (Pre-Stress)

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



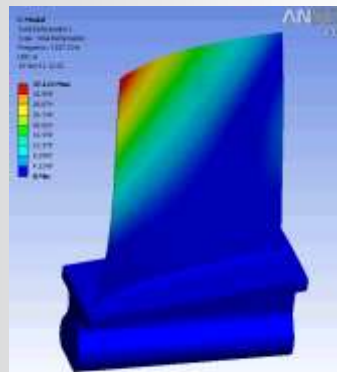
Modal Analysis



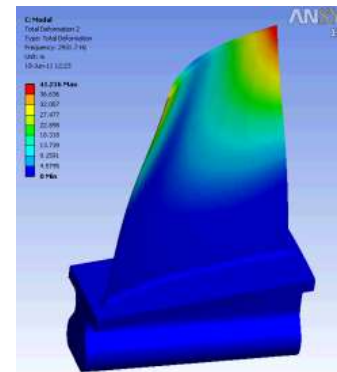
- Pre-Stressed Modal Analysis:
 - Eigen Frequencies and Vectors
 - Data for further MOR-Analysis

	Mode	<input checked="" type="checkbox"/> Frequency [Hz]
1	1.	1537.3
2	2.	2931.7
3	3.	5448.2
4	4.	7053.
5	5.	7567.1
6	6.	11155

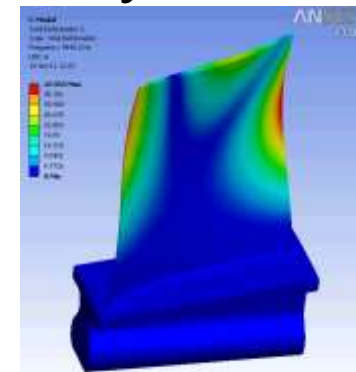
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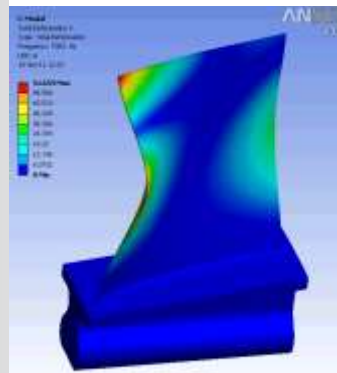
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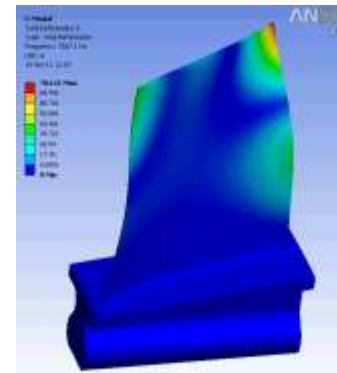
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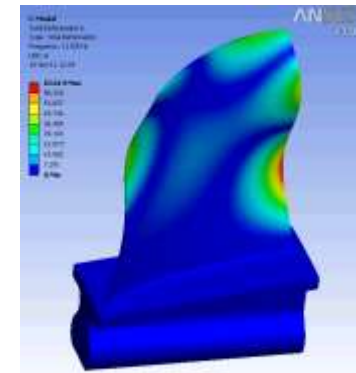
4



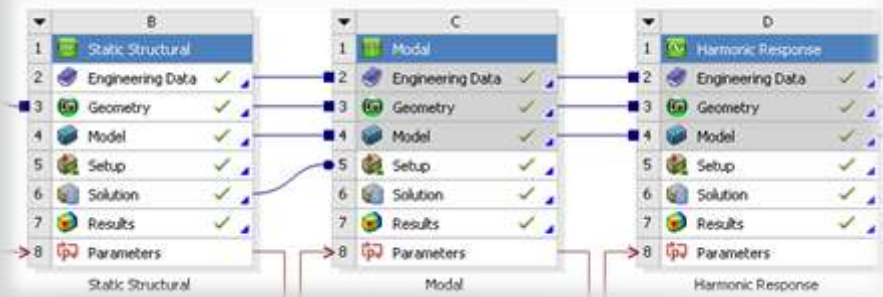
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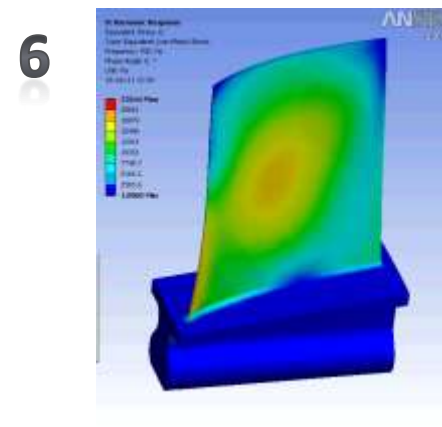
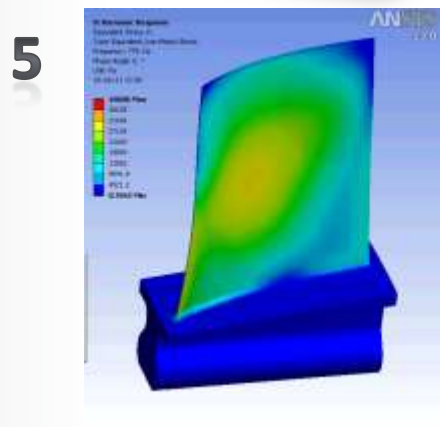
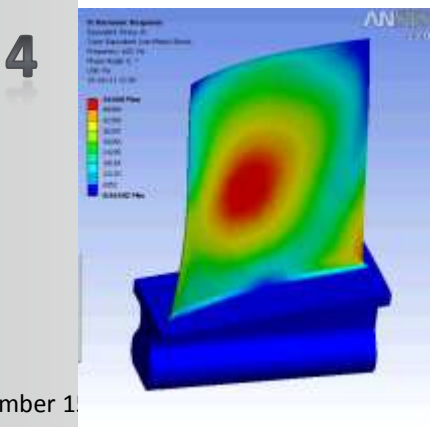
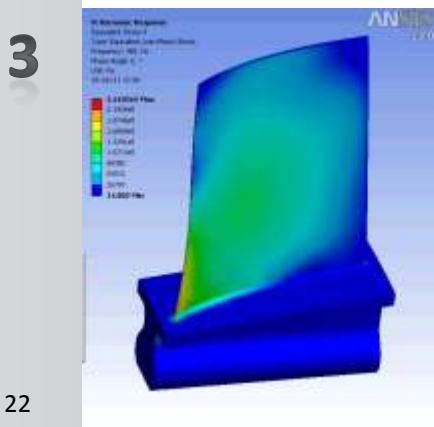
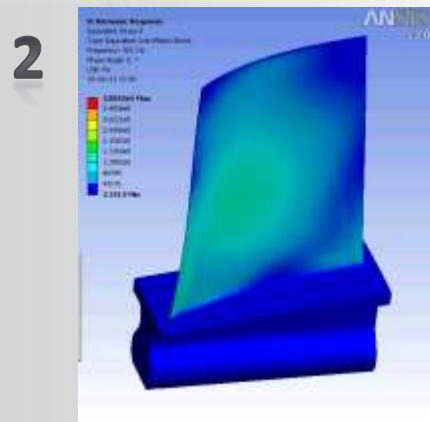
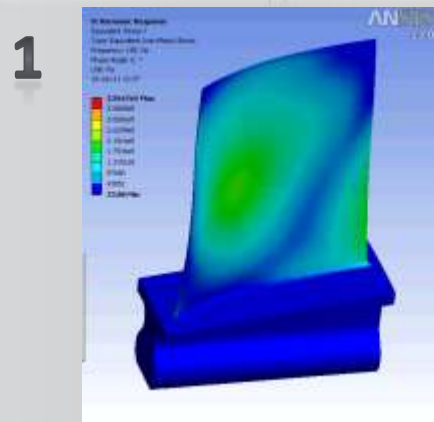
6



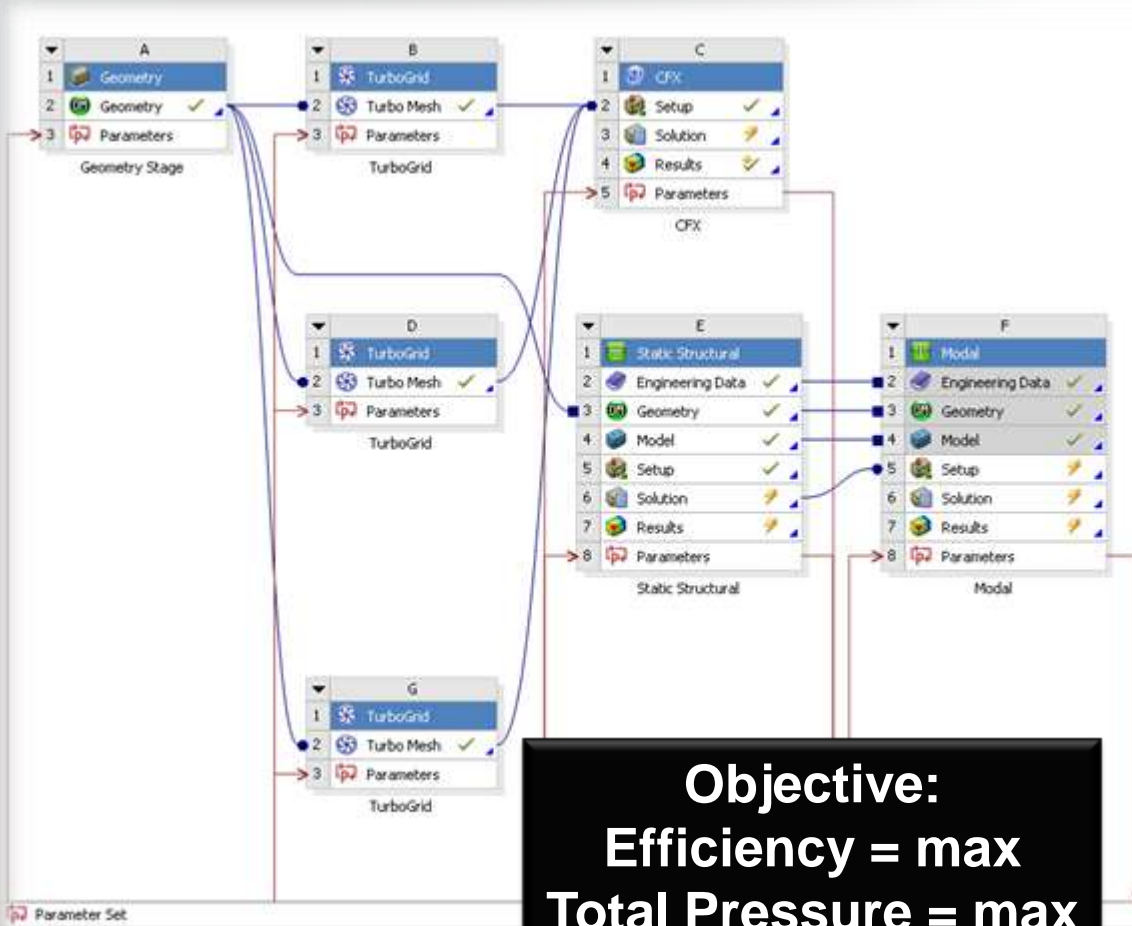
Forced Response Analysis



- Harmonic Analysis:
 - Modal Superposition
 - Fluid Load $F(\Omega)$
 - v. Mises Stress $\sigma_{v.M}(\Omega)$



Process Summary and Objectives



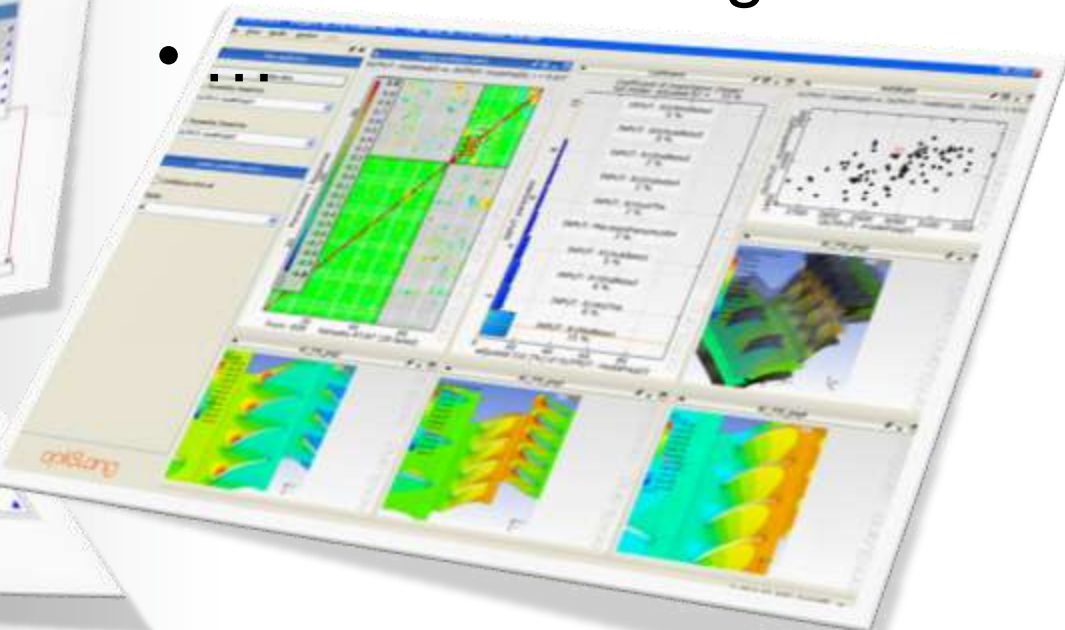
Objective:
Efficiency = max
Total Pressure = max
Stress < Limit
No Resonance

[-] Input Parameters		
+ Geometry Stage (A1)	47 (59) Input Parameter	
+ TurboGrid (B1)		
+ TurboGrid (D1)		
+ TurboGrid (G1)		
[-] CFX (C1)		
P16	nPitchS1	
P15	nPitchR1	
P14	nPitchIGV	
P17	myAirCP	
P18	myAirR	
P19	myomega	
P20	mymass	
P21	Ttin	11 Input Constraints
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	24 Output Parameter
[-] Output Parameters		
Charts		

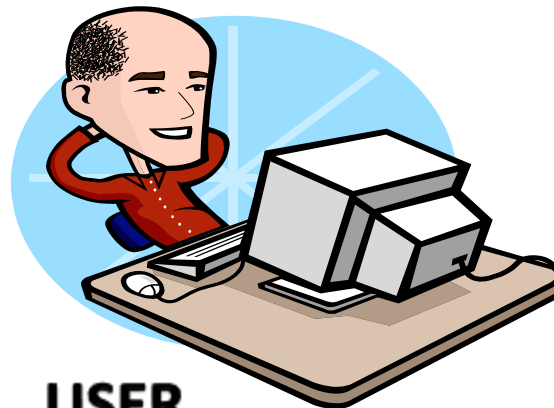
optiSLang Integration/Interface

optiSLang
optimizing structural language

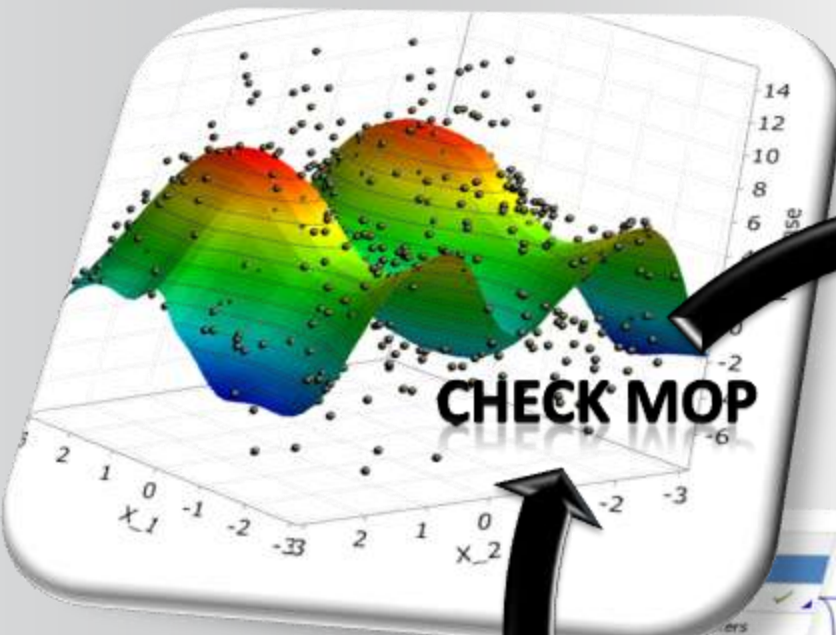
- Direct Integration
- Correlation Matrix
- Coefficient of Prognosis
- 2D and 3D Plot
- Anthill Plot
- Pictures of Design xxxx
- ...



Sensitivity Analysis

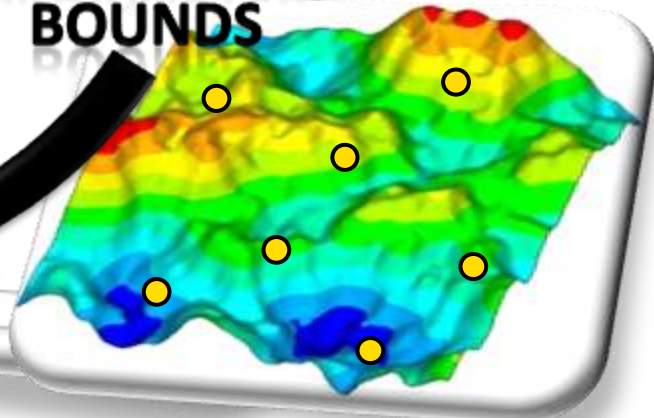


USER INTERACTION

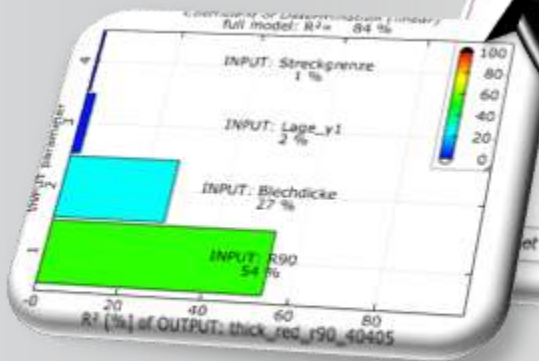


Parameter	Value
Pressure	83.3
ExitVel	26.2
FlowRate	208.3
HubVel1	-46.4
HubVel2	-25.8
HubVel3	-25.8
HubVel4	-26.1
HubVel5	-26.1
HubVel6	-26.1
HubVel7	-26.1
HubVel8	-26.1
HubVel9	-26.1
HubVel10	-26.1
HubVel11	-26.1
HubVel12	-26.1
HubVel13	-26.1
HubVel14	-26.1
HubVel15	-26.1
HubVel16	-26.1
HubVel17	-26.1
HubVel18	-26.1
HubVel19	-26.1
HubVel20	-26.1
HubVel21	-26.1
HubVel22	-26.1
HubVel23	-26.1
HubVel24	-26.1
HubVel25	-26.1
HubVel26	-26.1
HubVel27	-26.1
HubVel28	-26.1
HubVel29	-26.1
HubVel30	-26.1
HubVel31	-26.1
HubVel32	-26.1
HubVel33	-26.1
HubVel34	-26.1
HubVel35	-26.1
HubVel36	-26.1
HubVel37	-26.1
HubVel38	-26.1
HubVel39	-26.1
HubVel40	-26.1
HubVel41	-26.1
HubVel42	-26.1
HubVel43	-26.1
HubVel44	-26.1
HubVel45	-26.1
HubVel46	-26.1
HubVel47	-26.1
HubVel48	-26.1
HubVel49	-26.1
HubVel50	-26.1
HubVel51	-26.1
HubVel52	-26.1
HubVel53	-26.1
HubVel54	-26.1
HubVel55	-26.1
HubVel56	-26.1
HubVel57	-26.1
HubVel58	-26.1
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HubVel60	-26.1
HubVel61	-26.1
HubVel62	-26.1
HubVel63	-26.1
HubVel64	-26.1
HubVel65	-26.1
HubVel66	-26.1
HubVel67	-26.1
HubVel68	-26.1
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HubVel71	-26.1
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HubVel75	-26.1
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HubVel77	-26.1
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HubVel89	-26.1
HubVel90	-26.1
HubVel91	-26.1
HubVel92	-26.1
HubVel93	-26.1
HubVel94	-26.1
HubVel95	-26.1
HubVel96	-26.1
HubVel97	-26.1
HubVel98	-26.1
HubVel99	-26.1
HubVel100	-26.1

PARAMETER BOUNDS

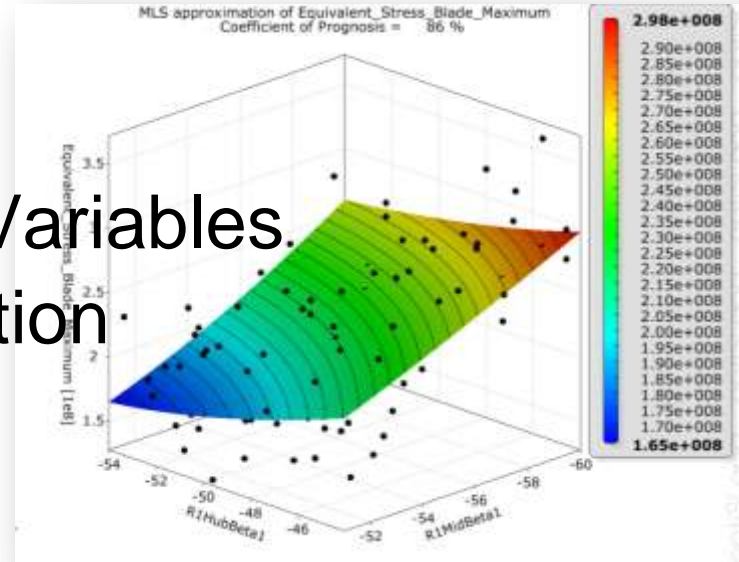
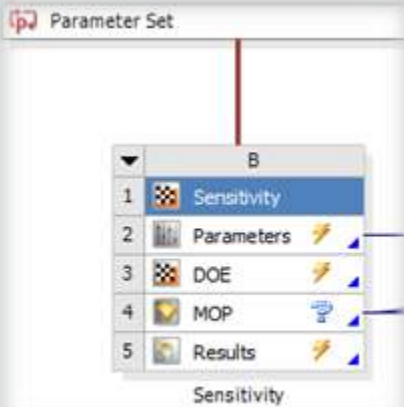


LHS-SAMPLING

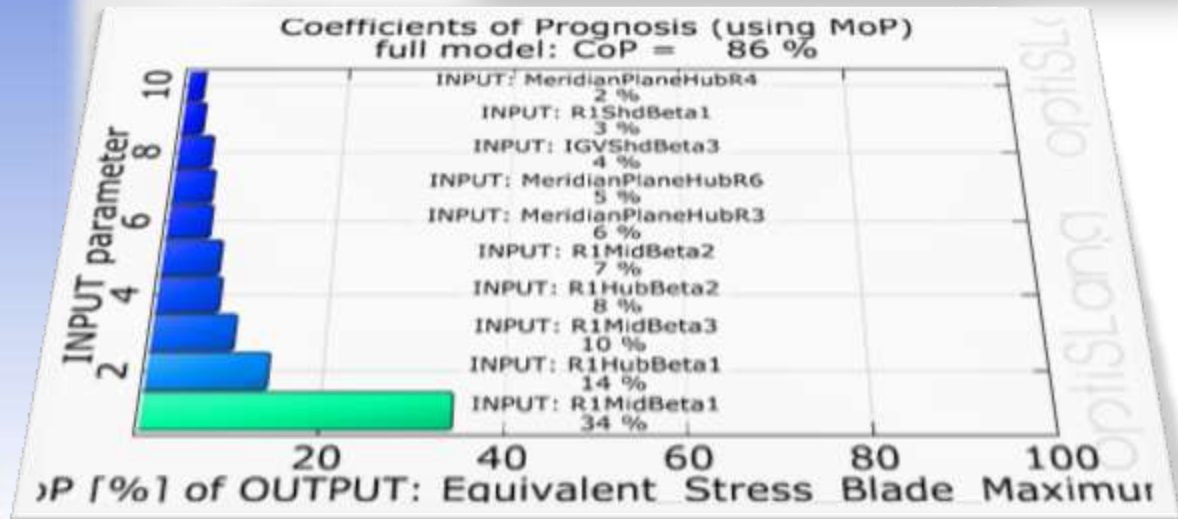
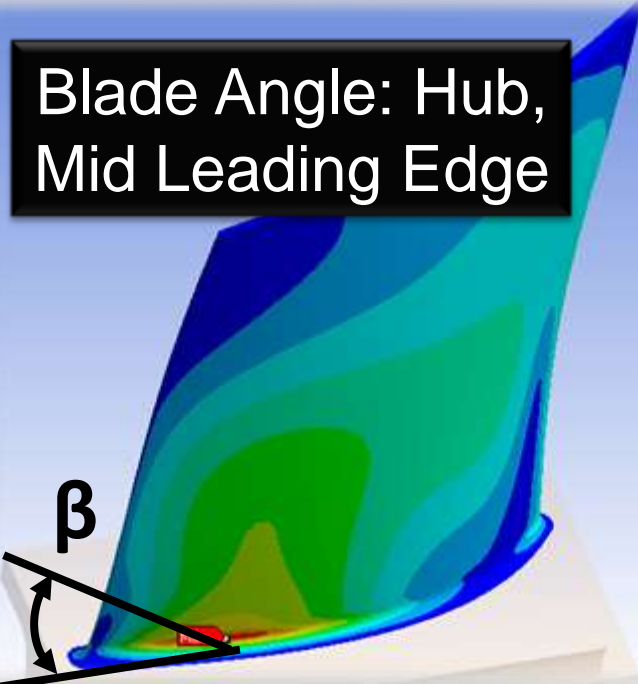


Sensitivity Analysis, Maximal Stress

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

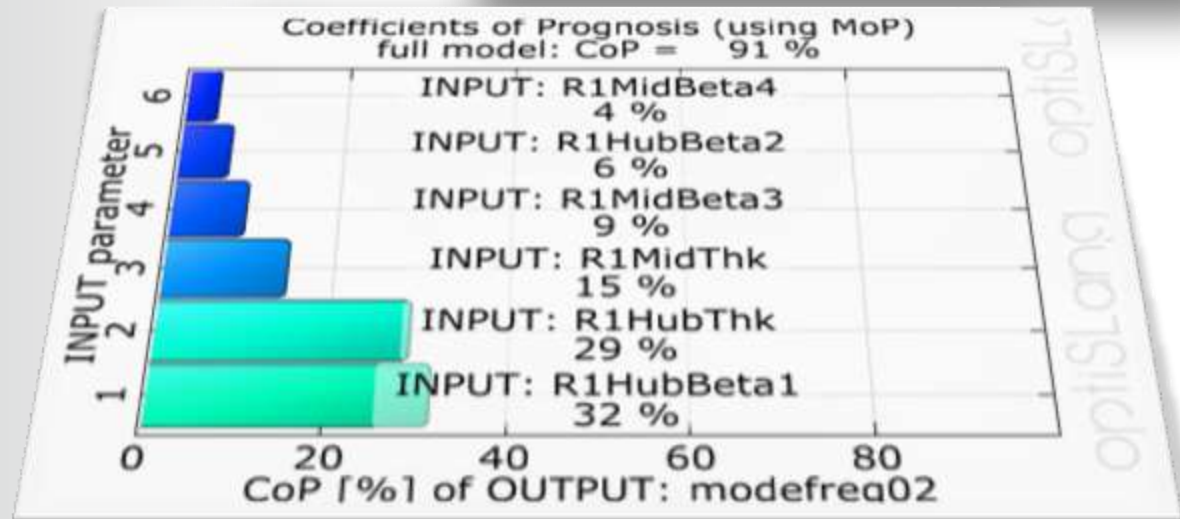
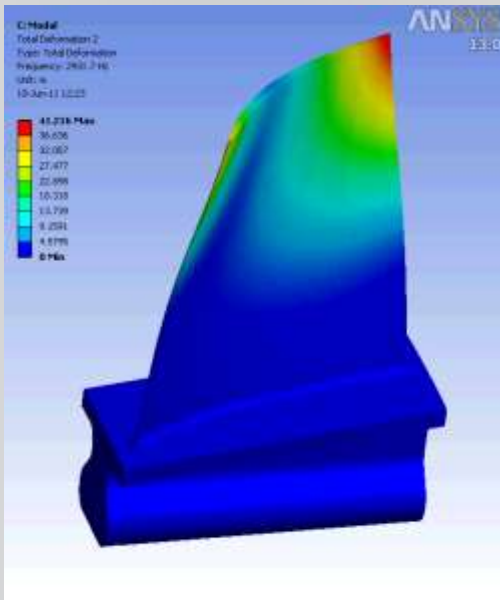
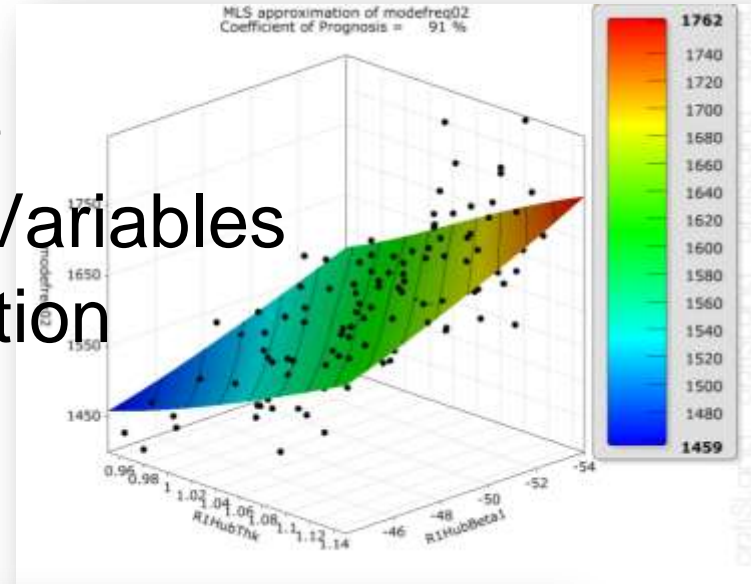
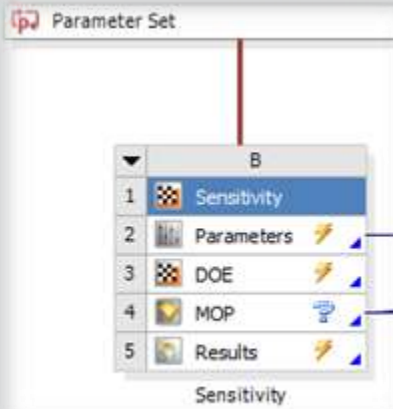


Blade Angle: Hub, Mid Leading Edge

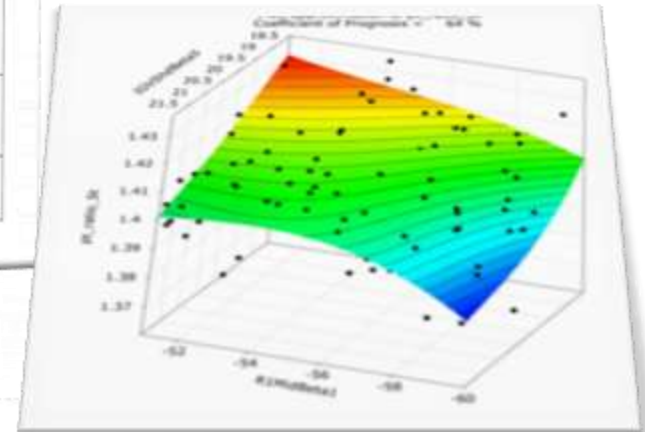
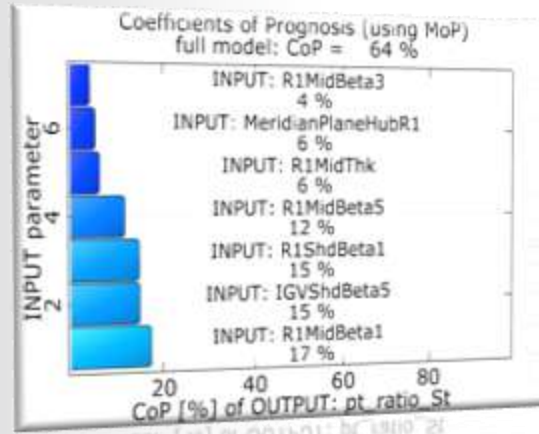
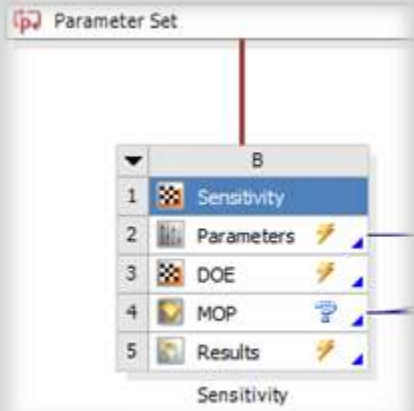


Sensitivity Analysis, Eigen Mode 2

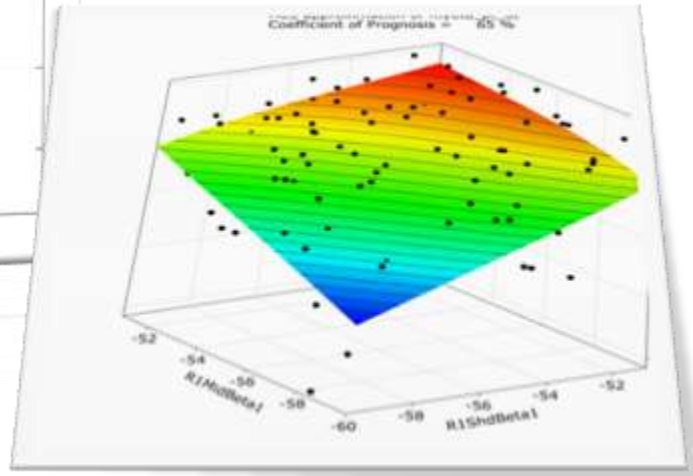
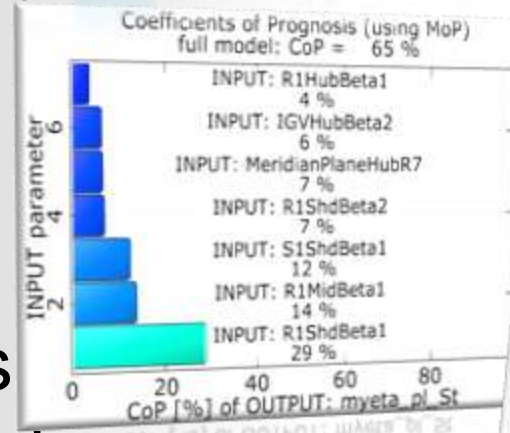
- CoP=91%
 - Statistic is reliable
 - Detect important Variables
 - Parameter Reduction
- MoP is plausible



Sensitivity Analysis, Aero Dynamic

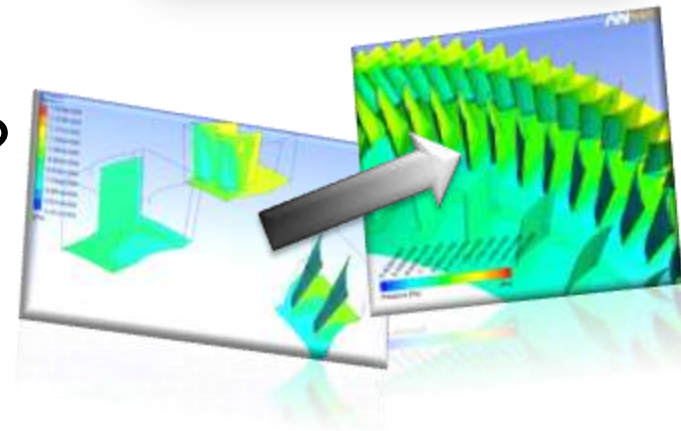
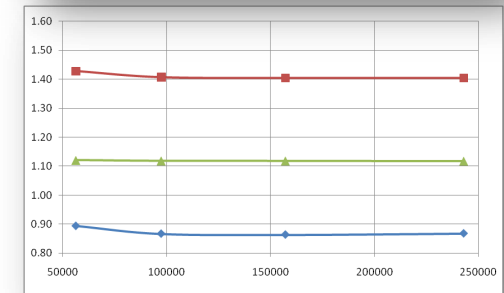
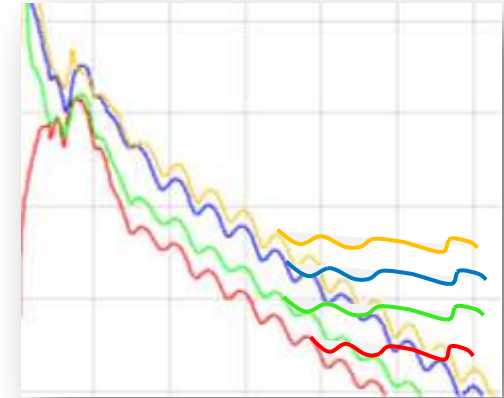


- CoP=64% and 65%
 - small value
 - Numerical error?
 - Model error?
- Important Variables
 - Parameter Reduction
- MoP is plausible



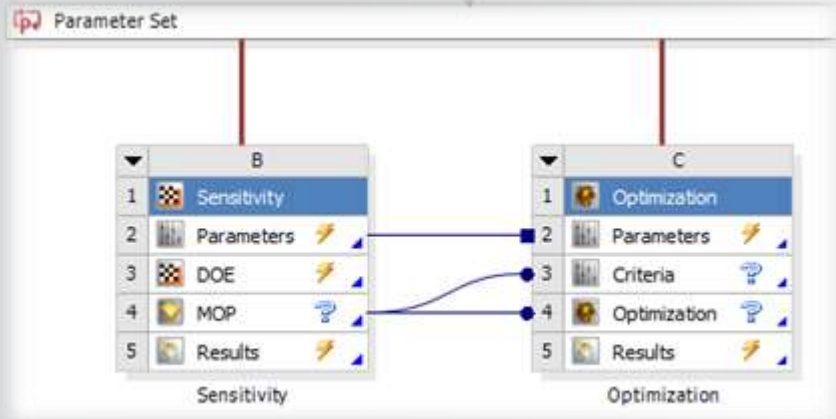
Trouble Shooting with small CoP

- Number of Evaluated Designs?
 - no, CoP(80)~CoP(150)!
- Numerical Error?
 - no, Best-Practice!
- Model Error?
 - yes, some Designs are transient!
- Overcome:
 - Full transient Simulation?
 - Transient Blade Row Method!?
 - Use Result „carefully“!



Design Optimization

Optimization Algorithms:



Evolutionary Algorithm

Gradient-Based Algorithms

Pareto Optimization

Adaptive Response Surface

Generic Algorithm

Which one is the best?

**Strategy is required!
and derived from SA**

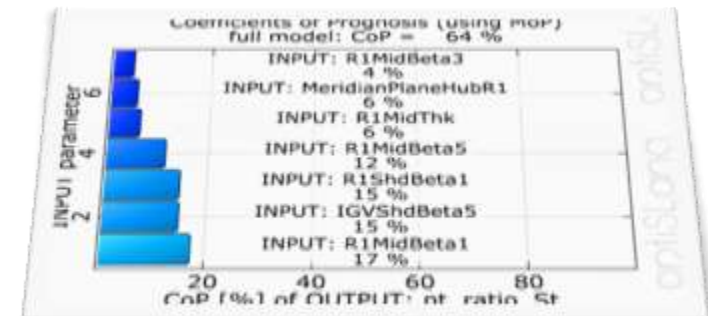
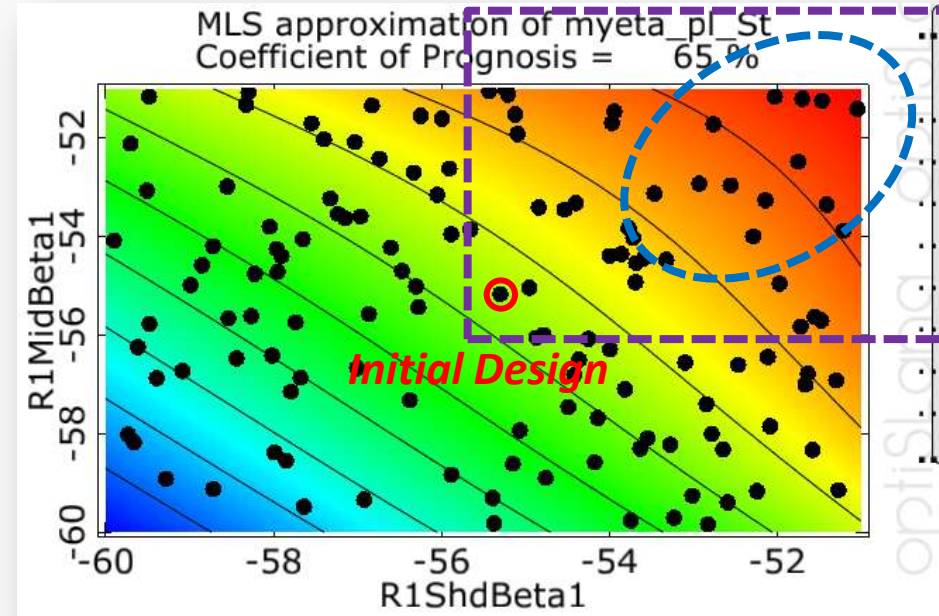
Design Optimization, Strategy

Sensitivity Analysis:

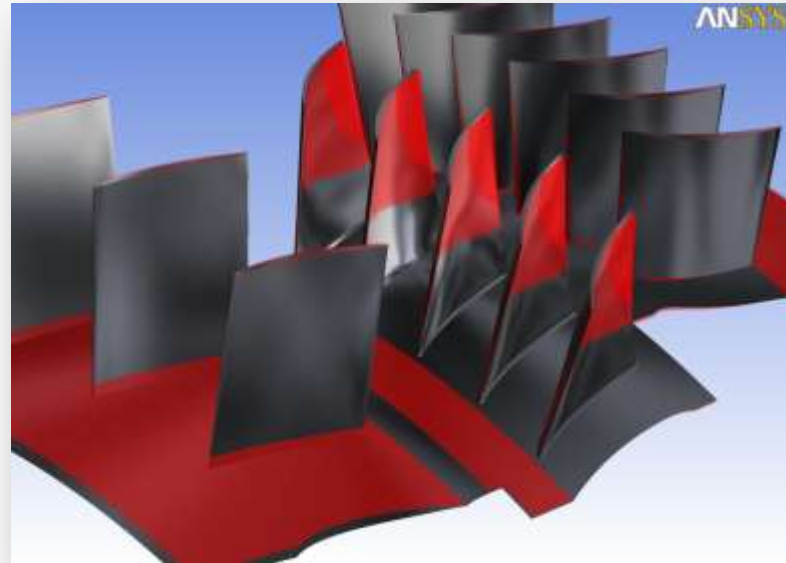
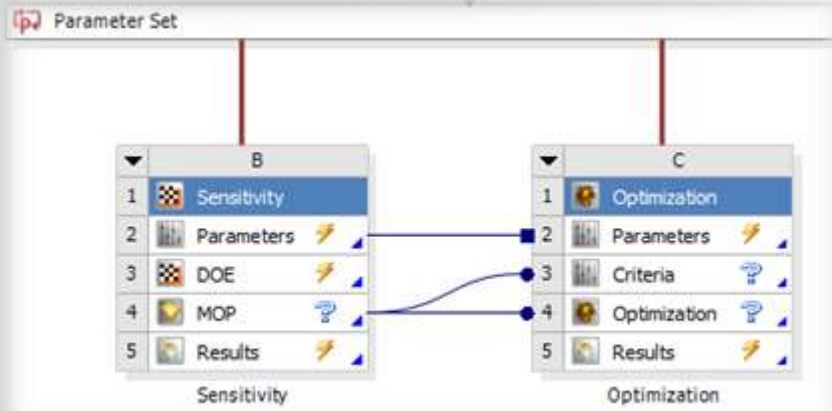
- Shows potential
- Indicates global optimum
- Parameter reduction
- Modify parameter space

Strategy:

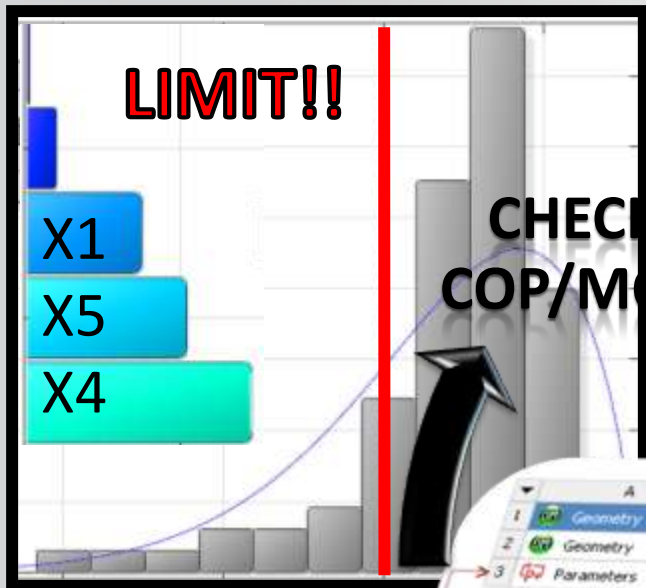
- Get best Design from SA/MoP
- Evaluate this Design and get initial for:
- Optimization in sub space: ARSM
 - Small Number of Parameter
 - Global Optimum



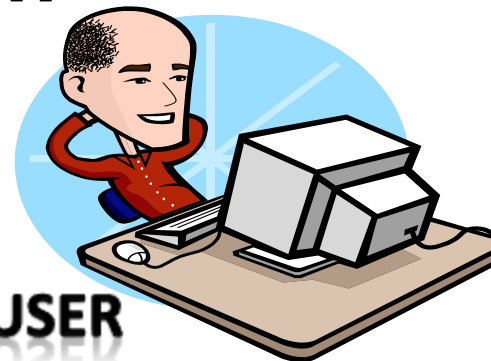
Design Optimization, Summary



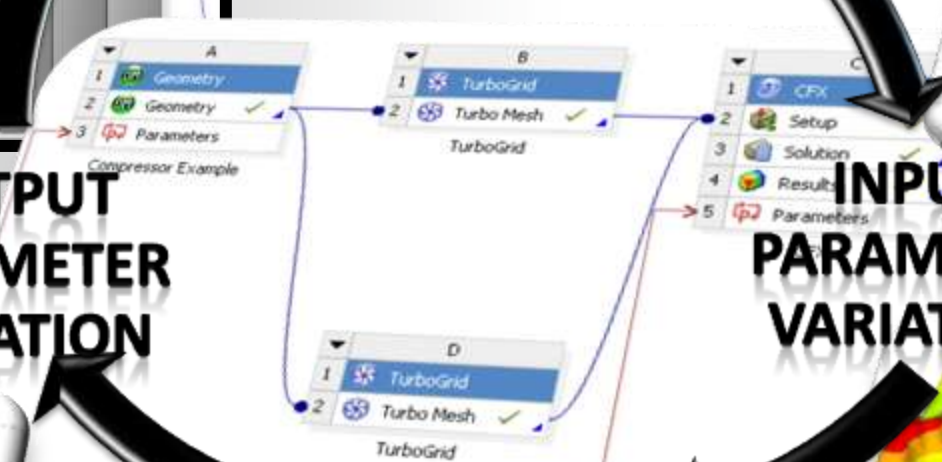
	Initial Design	Best Design SA	Best Design Solved (MoP)	Best Design ARSM
Efficiency [%]	87.0	88.0	88.9 (91.0)	88.9
p_{tot} Ratio [-]	1.41	1.41	1.41 (1.44)	1.41
Max. Stress [MPa]	219	235	232 (230)	239
#Designs	1	150	1 (0)	100



CHECK COP/MOP

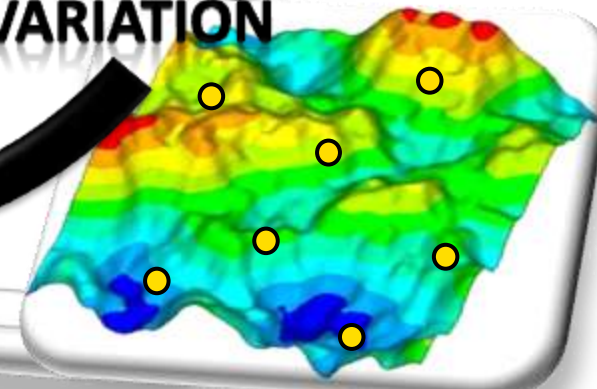
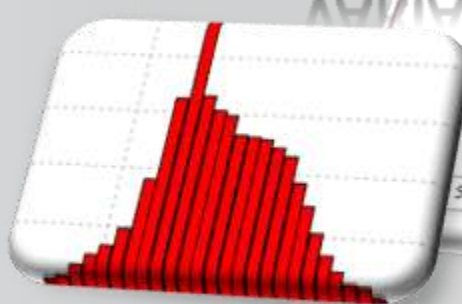
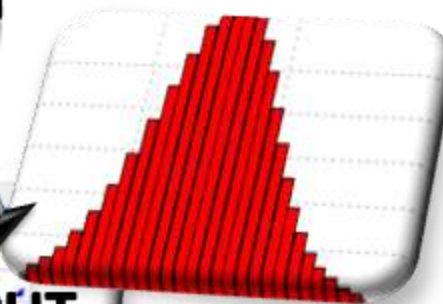


USER INTERACTION



OUTPUT PARAMETER VARIATION

INPUT PARAMETER VARIATION



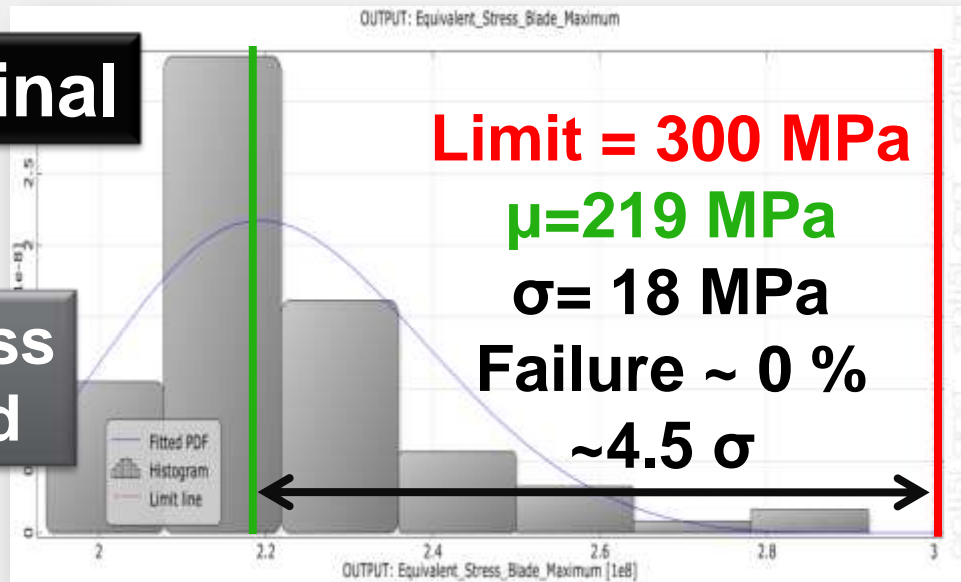
STATISTICAL LHS-SAMPLING

Robustness, Maximum Stress

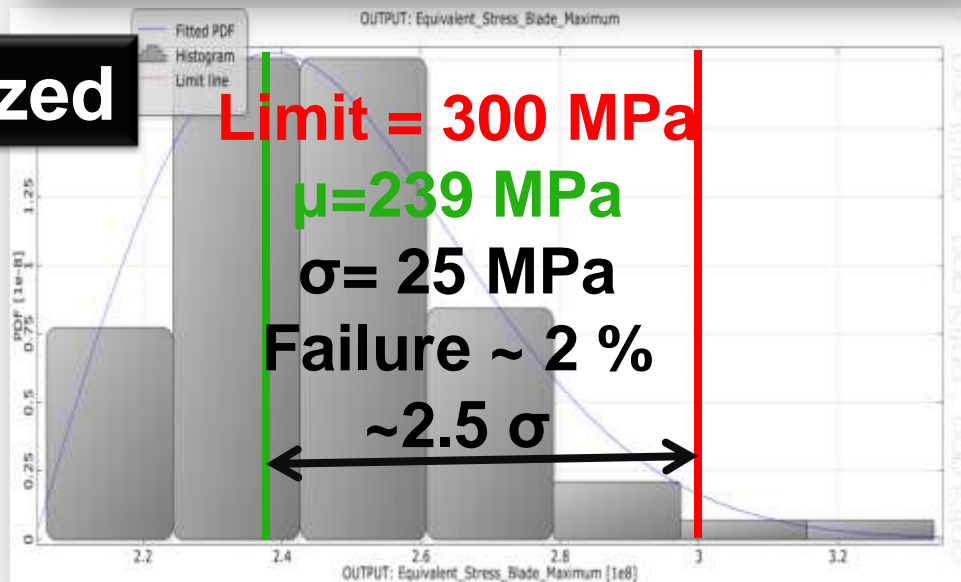
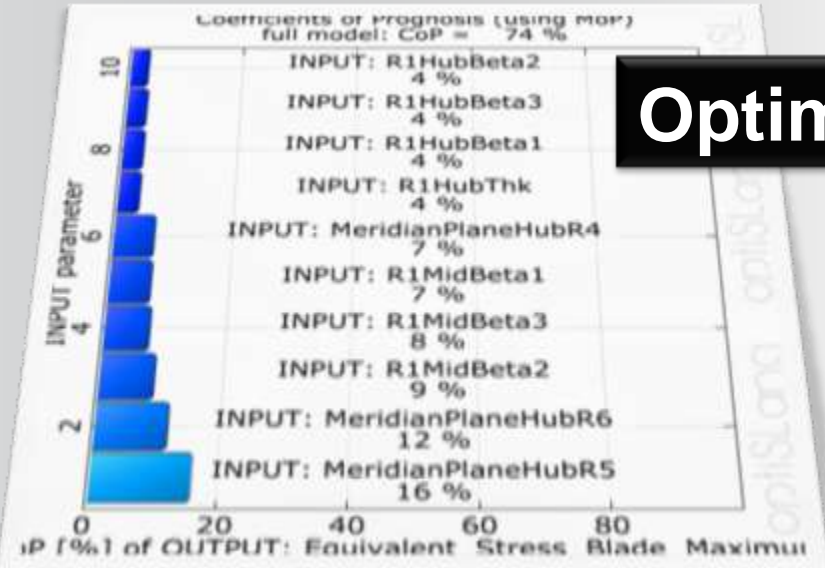


Original

Robustness decreased



Optimized

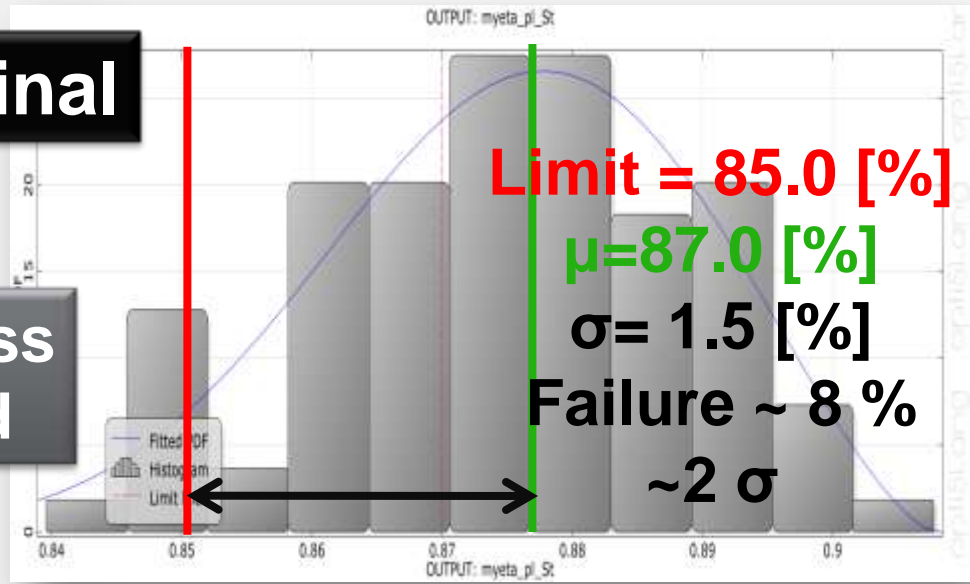


Robustness, Efficiency

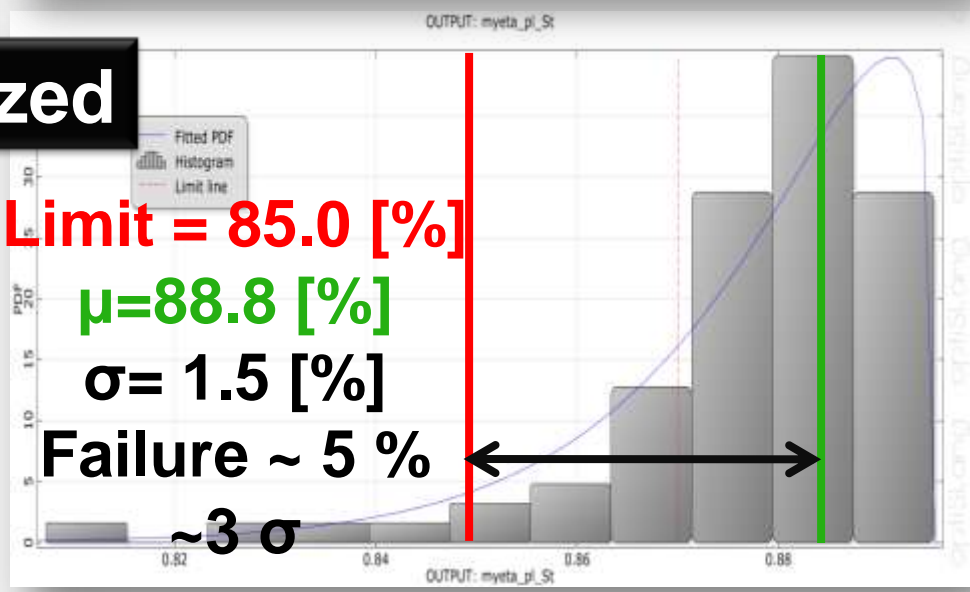
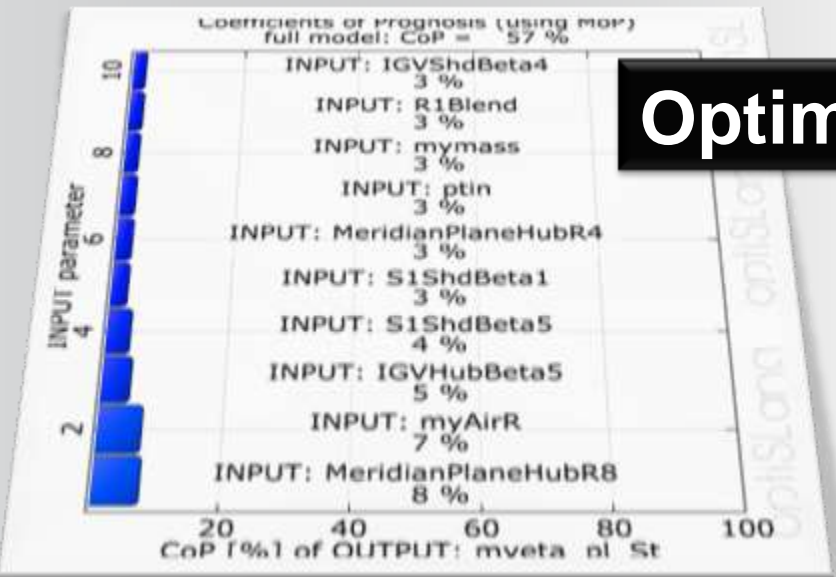


Original

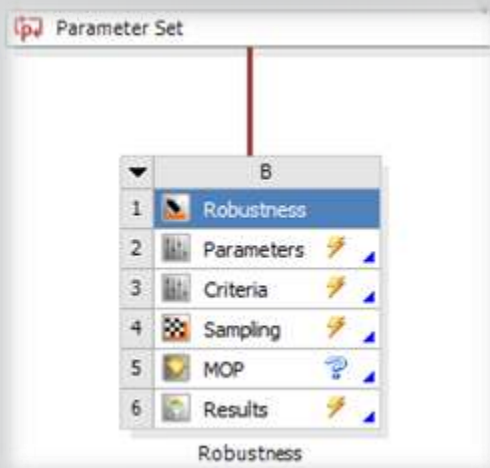
Robustness increased



Optimized



Robustness, Total Pressure Ratio

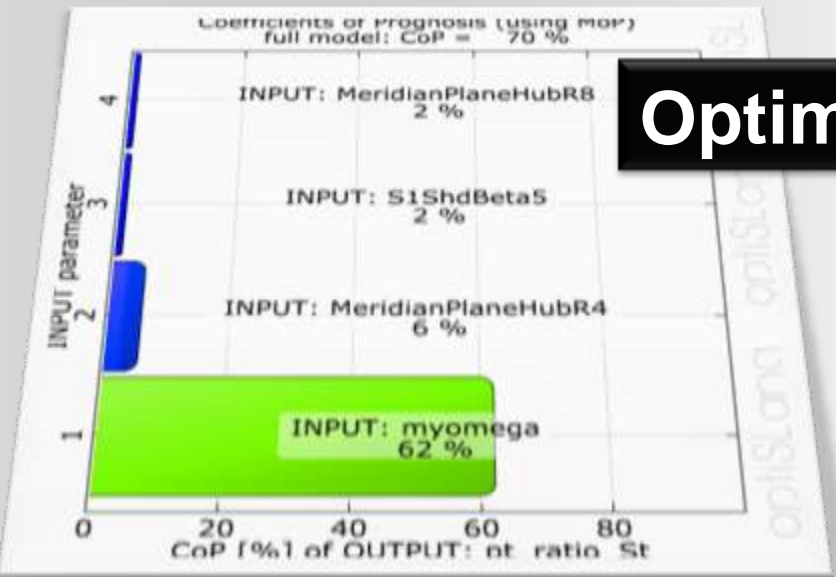


Original

Robustness approx. equal



Optimized



Summary

optiSLang
 optimizing structural language

**AUTOMATIZATION
 OPTIMIZATION**

**MULTIPHYSICS
 COUPLING**

**BREADTH
 DEPTH**

