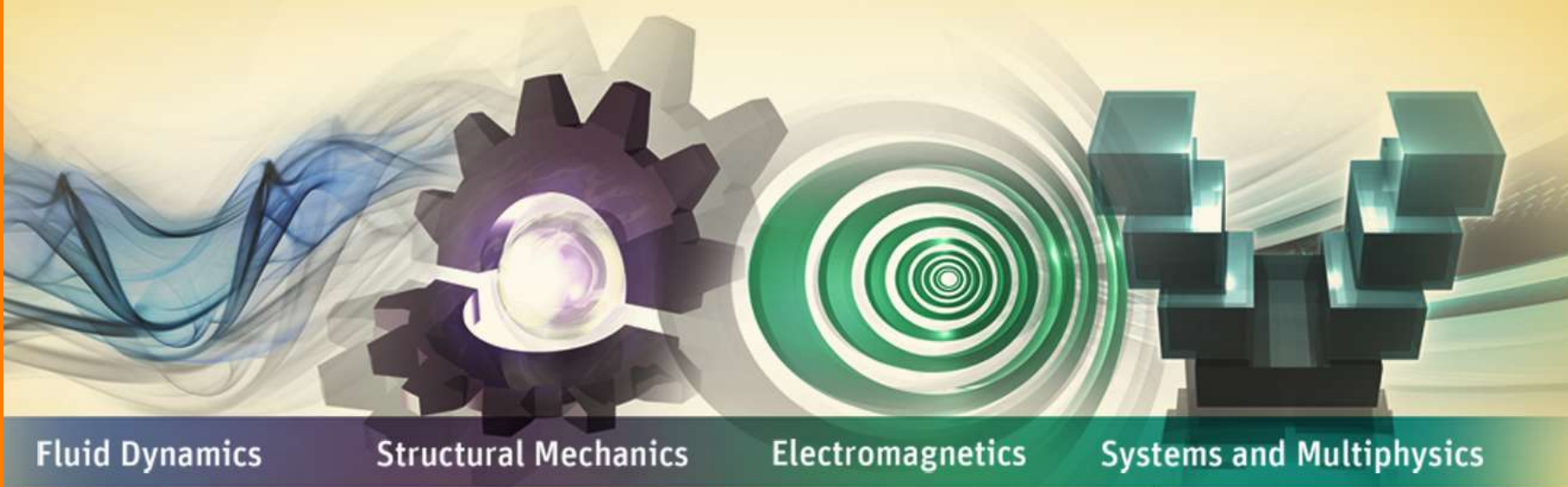


Robust Design Optimization of an Axial Compressor



Fluid Dynamics

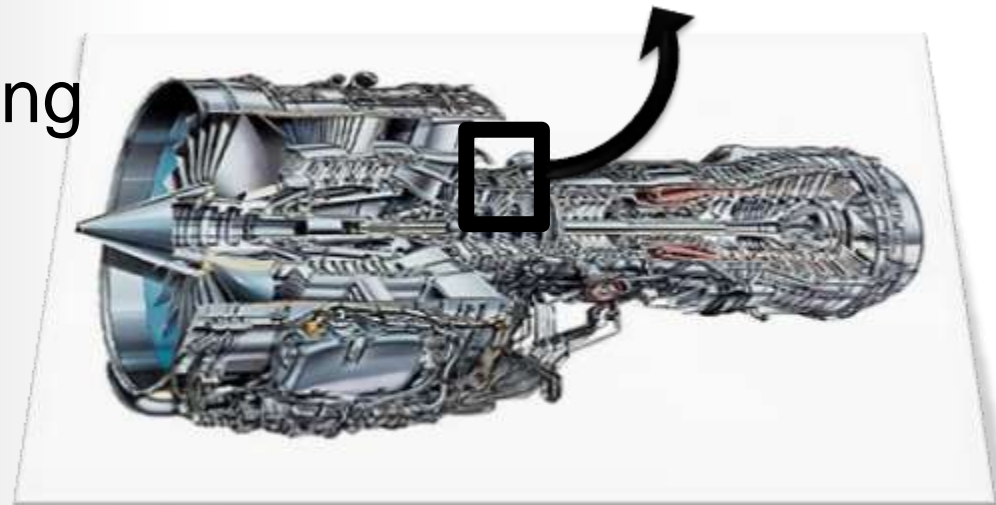
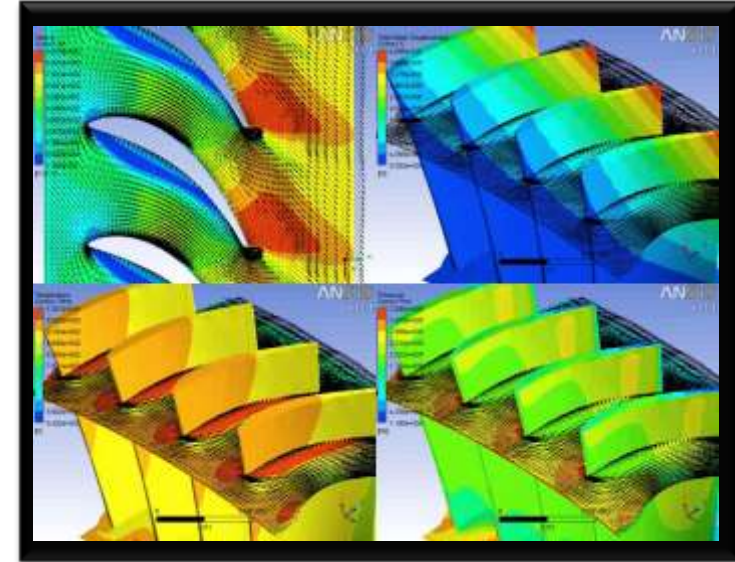
Structural Mechanics

Electromagnetics

Systems and Multiphysics

Johannes Einzinger
ANSYS Germany GmbH

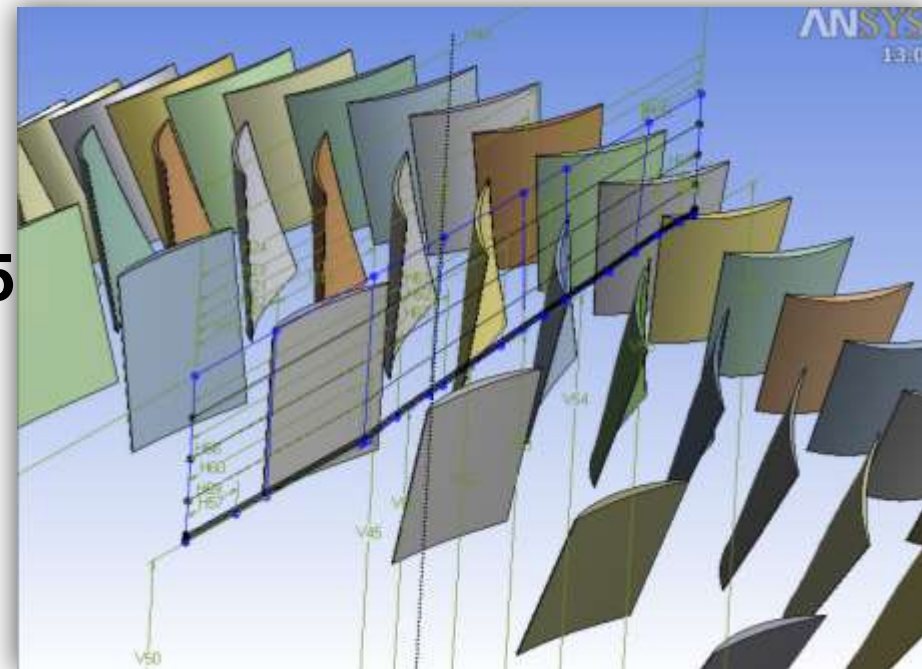
- Turbo Machines show:
 - Rotating and stationary Parts
 - Transient Flow Field
 - Choke, Stall...
 - ...
 - Dynamic Blade Loading
 - ...



**High Requirement
for Optimization**

Primary Design, PCA Engineers

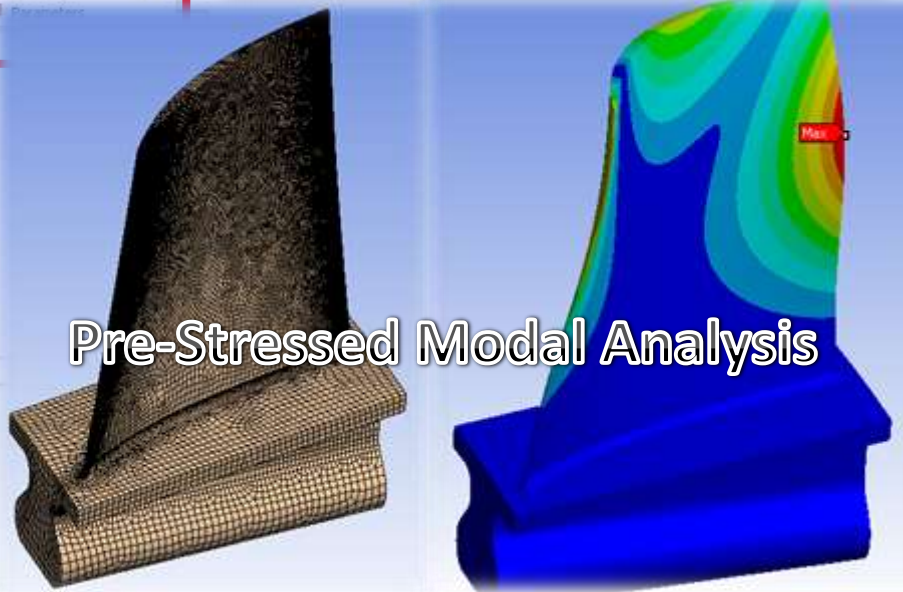
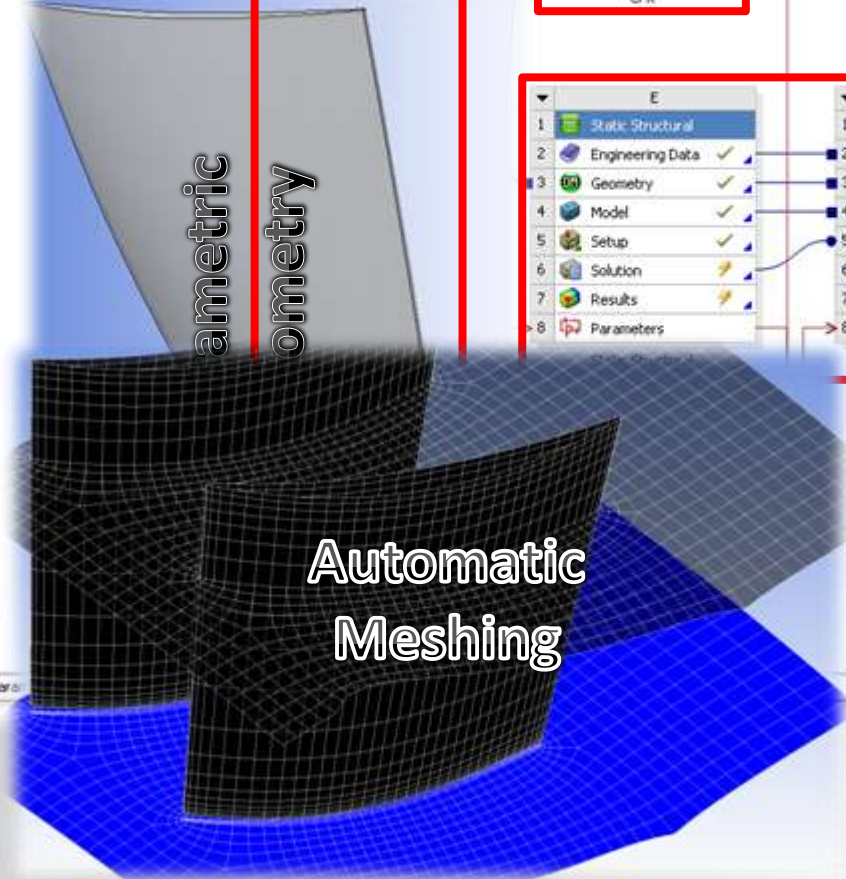
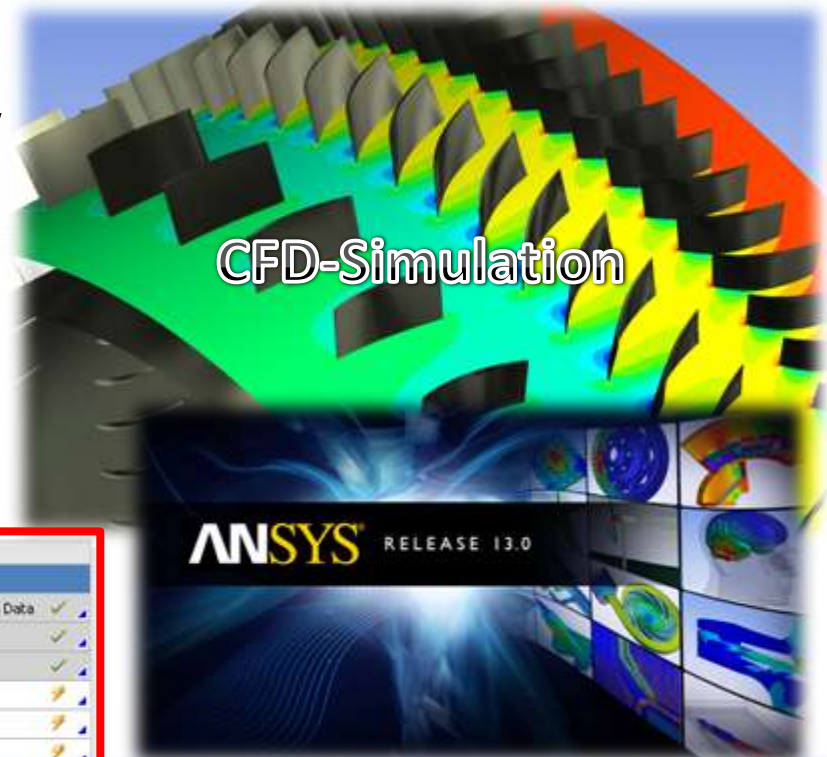
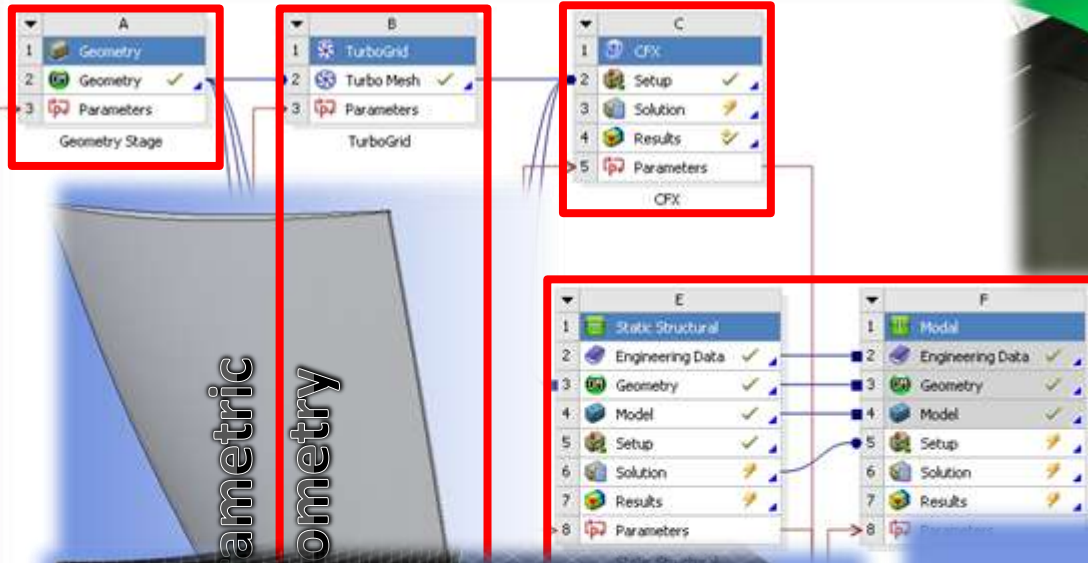
- 1.5 Stage Axial Compressor
- IGV(n=37)
- R1 (n=71, Gap @ Shroud 2% Span)
- S1 (n=91, Gap @ Hub 2% Span)
- Pressure Ratio $\Pi=1.4$
- Mass Flow Rate 10.6 [kg/s]
- Diameter $d = 0.525$ [m]
- Rot. Vel. $\Omega = 9300$ [rpm]
- Blade Mach Number $M_u=0.75$
- Specific Speed $n_s = 1.3$
- Specific Diameter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



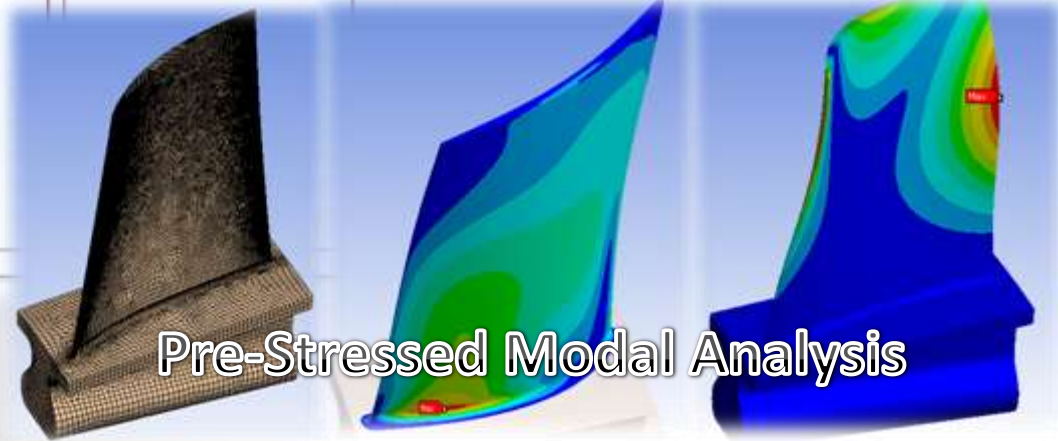
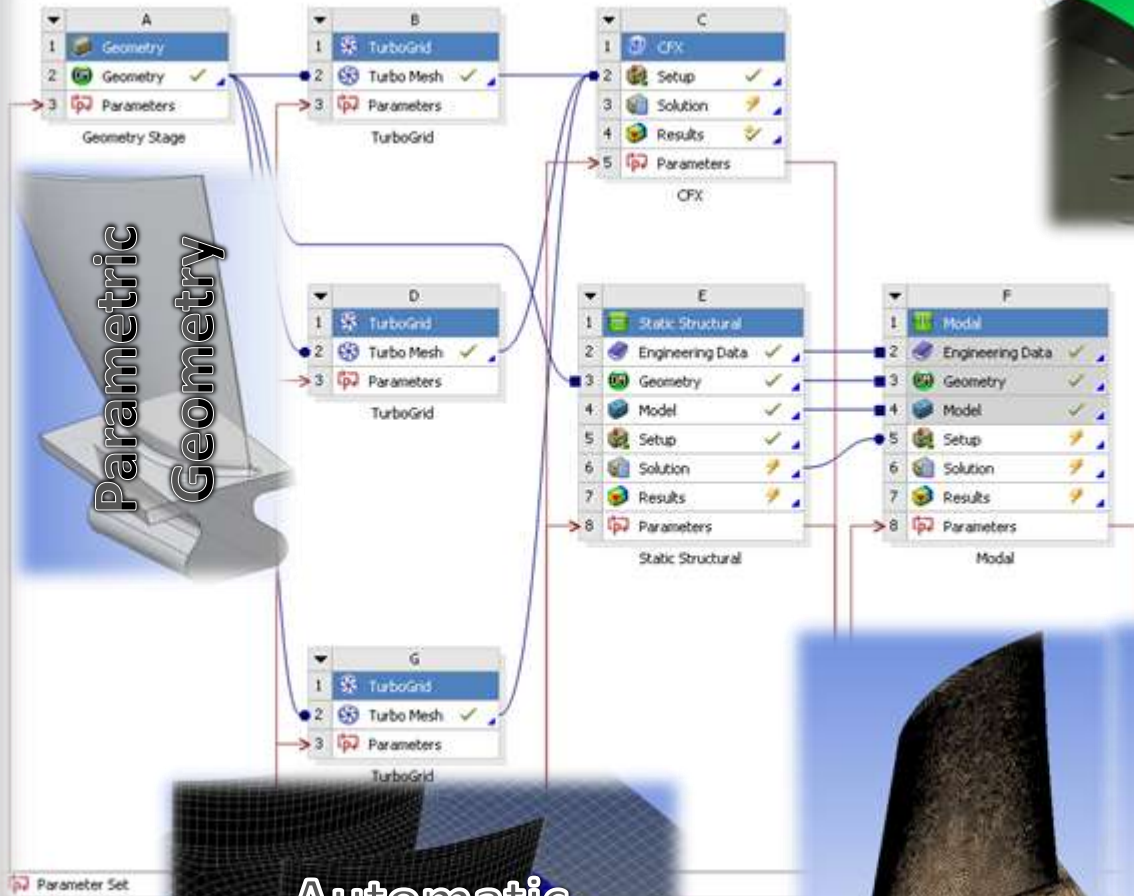
- **Parametric Geometry**
- **Automatic Meshing**
- **Automatic Solution**
 - Fluid Mechanics
 - Structural Dynamics
- **Sensitivity Analysis**
- **Design Optimization**
- **Robustness Evaluation**



Process Overview



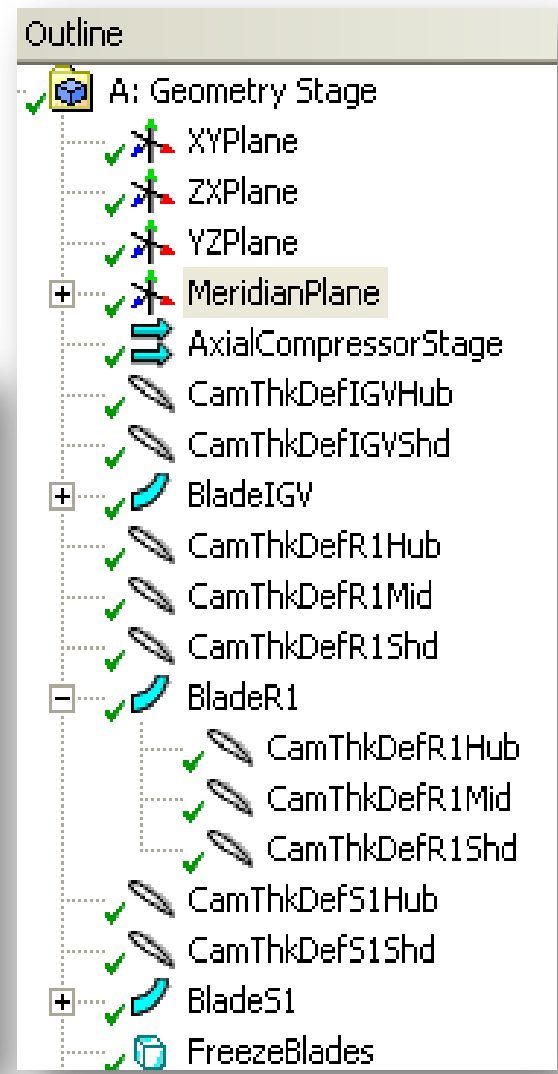
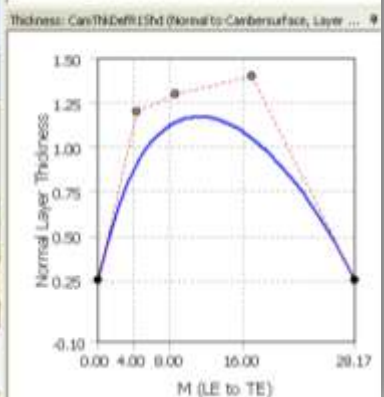
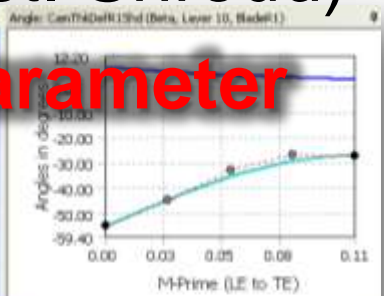
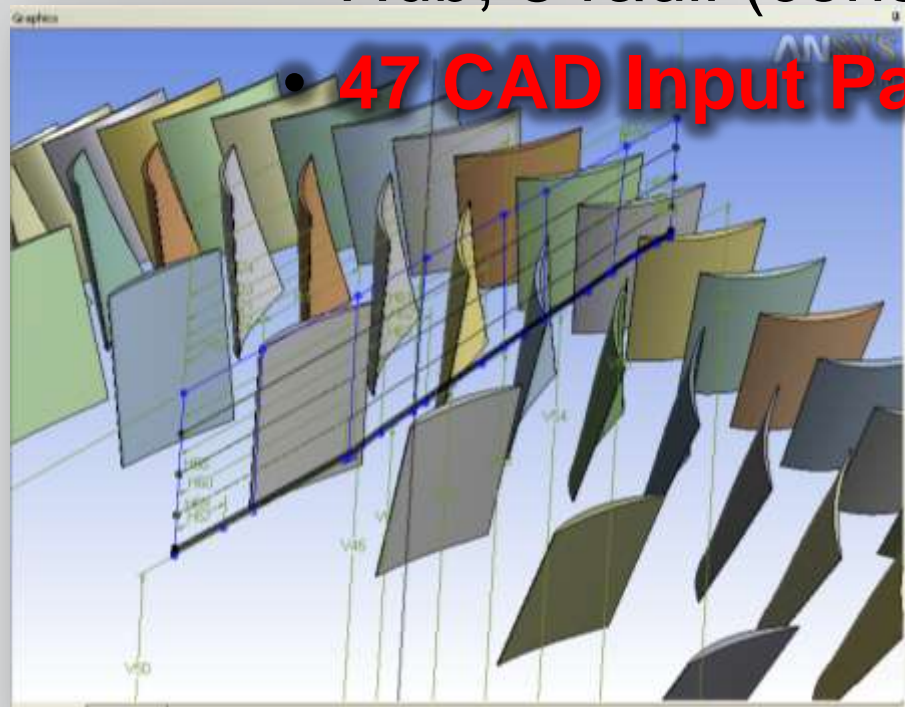
Process Overview



Geometry, Aero Dynamic

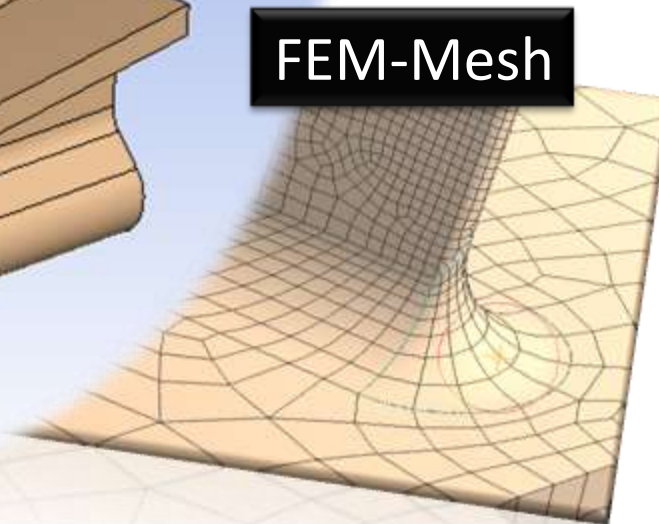
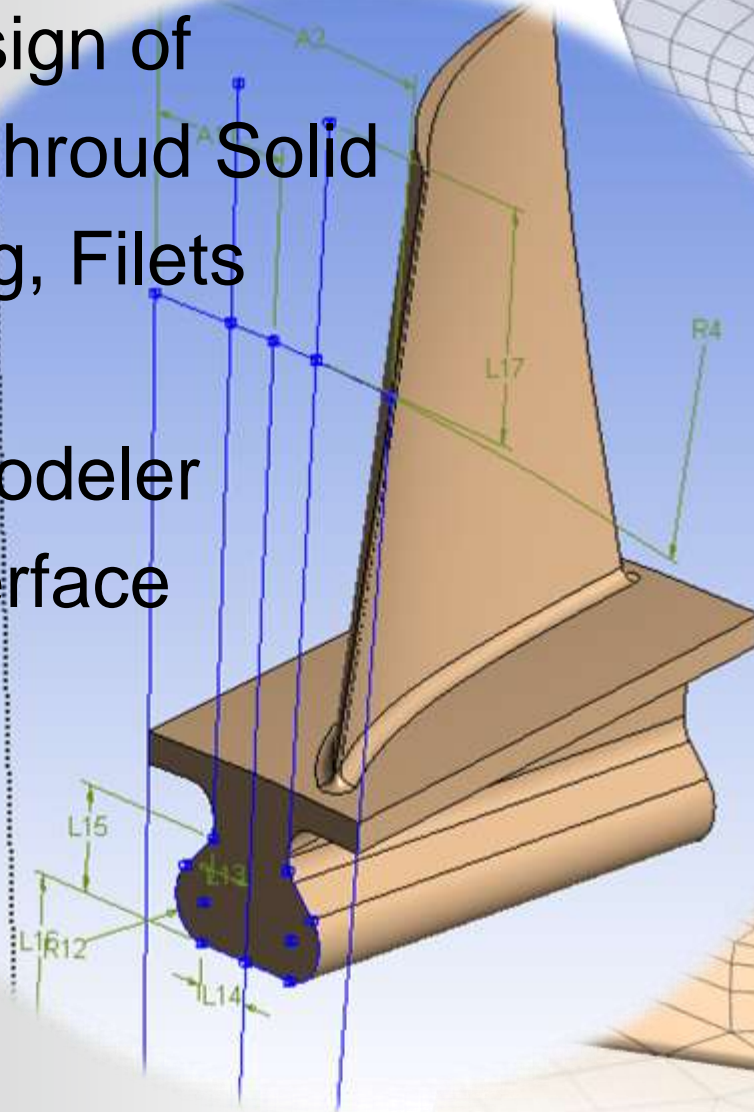
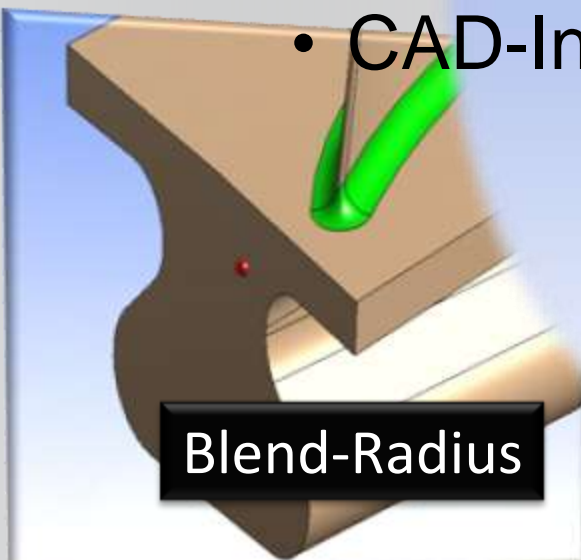
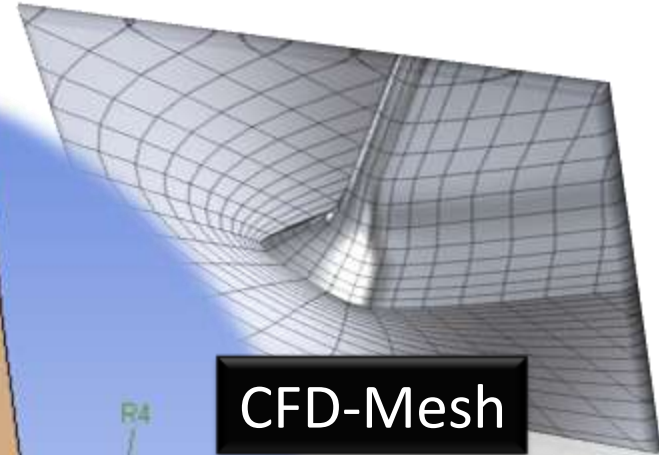
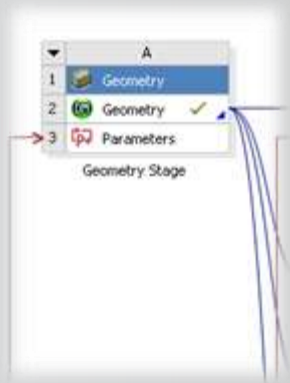
- Camber/Thickness for
 - IGV, R1, S1; 2-3 Layers
 - 5 β_i per Layer, 3xThk
- Hub, 8 radii (const. Shroud)

47 CAD Input Parameter



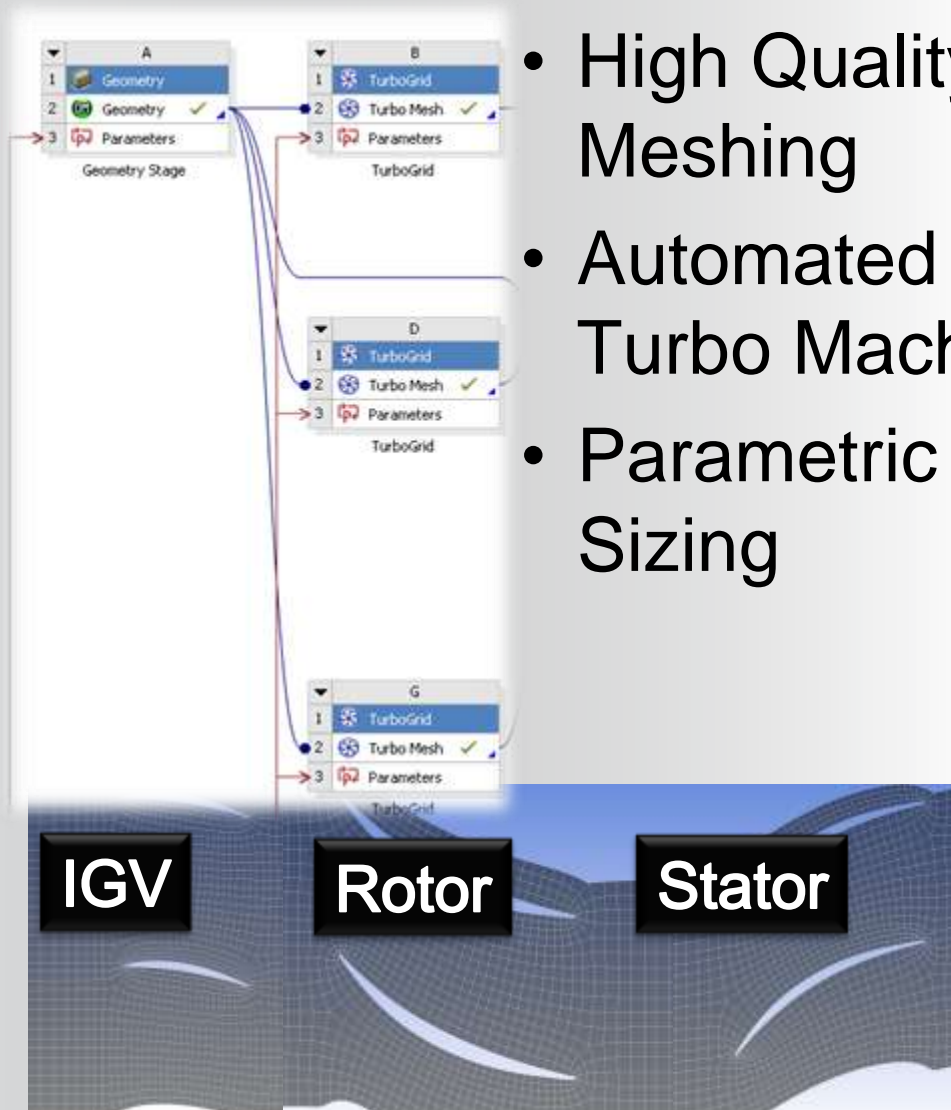
Geometry, Blade Design

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



Meshing, TurboGrid

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

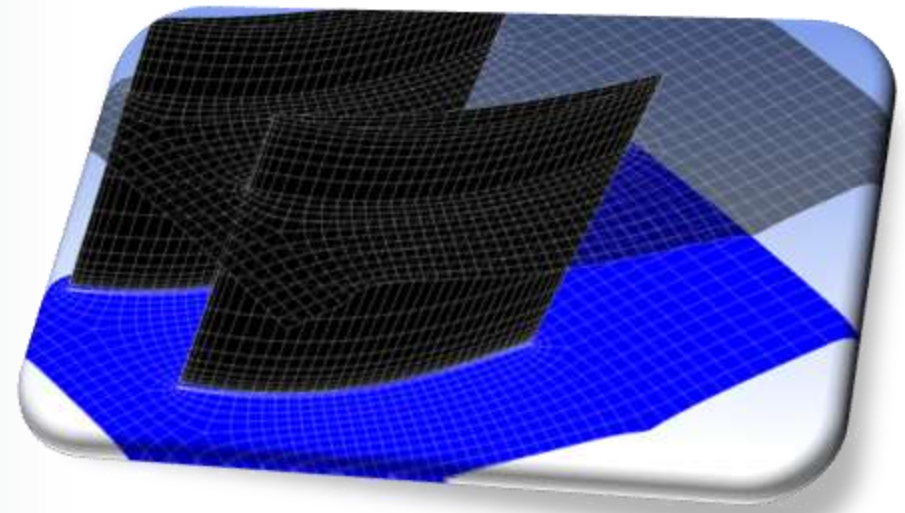


Expression Editor

Expressions

- MeshSizeFactor J
- MinMeshAngle $minVal(Minimum\ Face\ Angle)@Outlet$

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
3	TurboGrid (B1)			
4	P1	MeshSizeFactor	1	
*	New input parameter	New name	New expression	
6	Output Parameters			
7	TurboGrid (B1)			
8	P2	MinMeshAngle	10.015	degree
*	New output parameter		New expression	



Meshing, General

The screenshot displays the ANSYS Workbench environment. On the left, a project tree shows stages A through G, each containing Geometry, TurboGrid, Turbo Mesh, and Parameters. Stage A is labeled 'Geometry Stage' and stages B, D, and G are labeled 'TurboGrid'. Stage E is labeled 'Static Structural'. The central 3D model shows a turbine blade with a hex-dominant mesh. The right side shows the 'Outline' tree with 'Mesh' expanded, listing various meshing options like Match Control, Face Staging, and Mapped Face Meshing. Below the 3D model is the 'Details of Mesh' panel, showing settings for Defaults, Sizing, and Transition. At the bottom right is a bar chart titled 'Number of Elements' vs 'Element Metrics'.

Details of Mesh

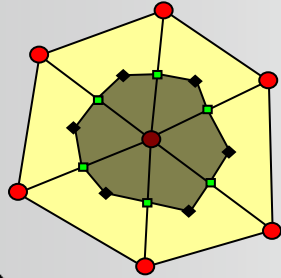
Category	Property	Value
Defaults	Physics Preference	Mechanical
	Relevance	0
Sizing	Use Advanced Size Function	On: Proximity and Curvature
	Relevance Center	Coarse
	Initial Size Seed	Active Assembly
	Smoothing	Maximize
	Transition	
	Span Angle Curvature N	55713.00
	Span Angle Curvature S	50000.00
Transition	Min Size	
	Max Face Size	
	Max Size	
	Growth Rate	
	Minimum Edge Length	

Number of Elements vs Element Metrics

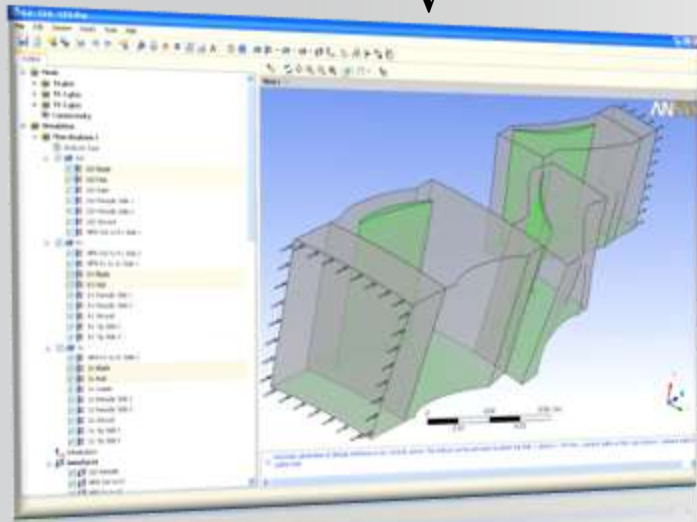
Element Metric	Tet20	Hex20	Wed25	Pyr13
0.00	~1000	~1000	~1000	~1000
0.13	~1000	~1000	~1000	~1000
0.25	~1000	~1000	~1000	~1000
0.38	~1000	~1000	~1000	~1000
0.50	~1000	~1000	~1000	~1000
0.63	~1000	~1000	~1000	~1000
0.75	~1000	~1000	~1000	~1000
0.88	~1000	~1000	~1000	~1000
1.00	~1000	~1000	~1000	~1000

- 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

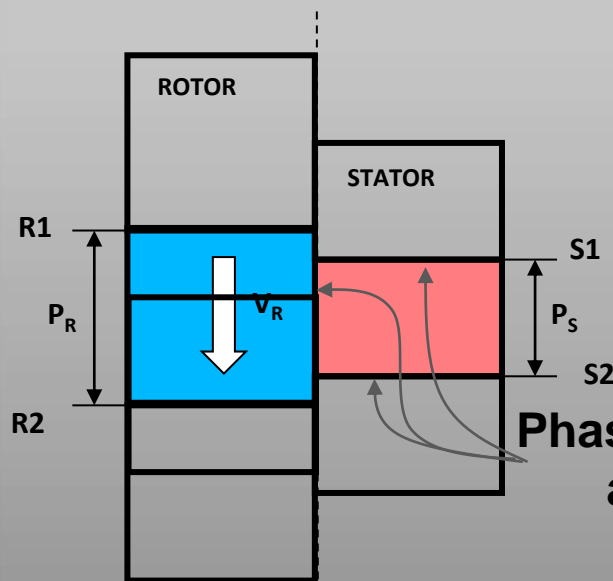
Fourier Transformation

**Shape Correction
Phase Shift**

Harmonic Transformation

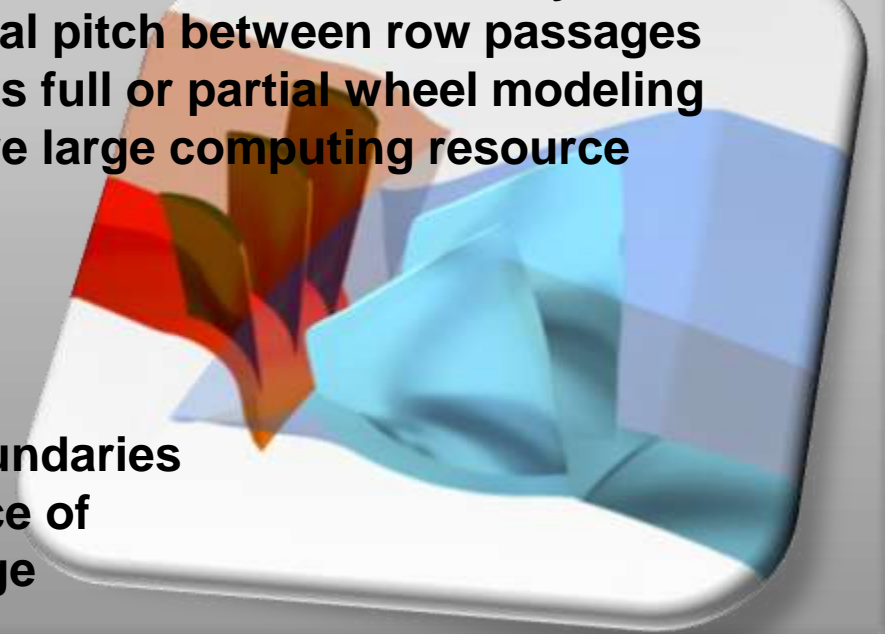
$f(t) \rightarrow F(\Omega)$
R&D

unequal pitch



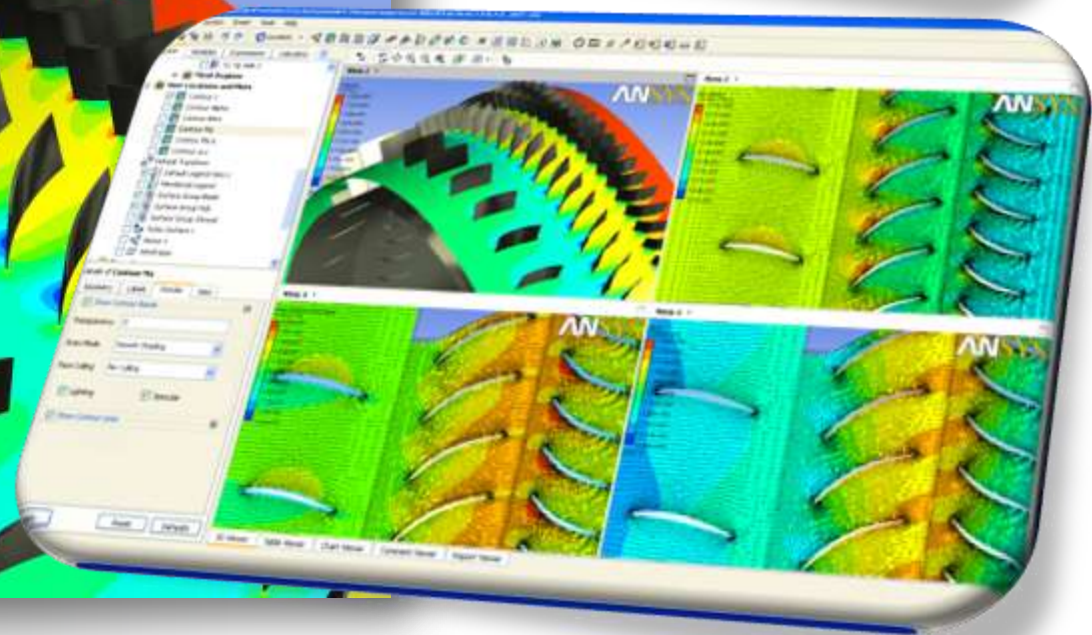
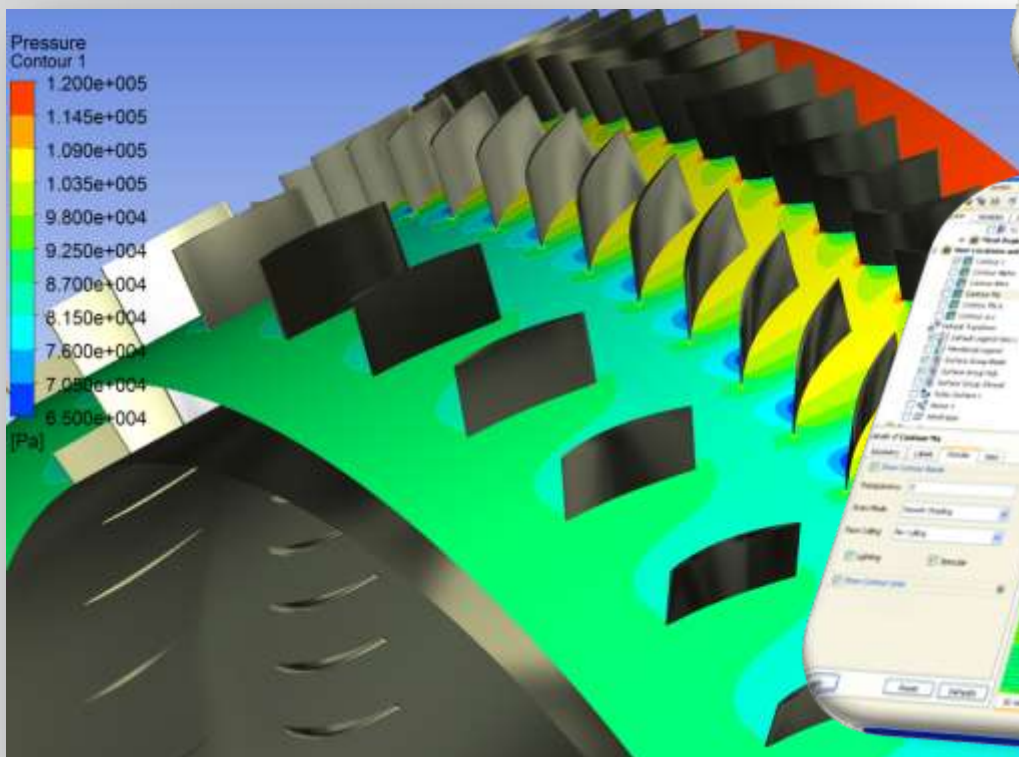
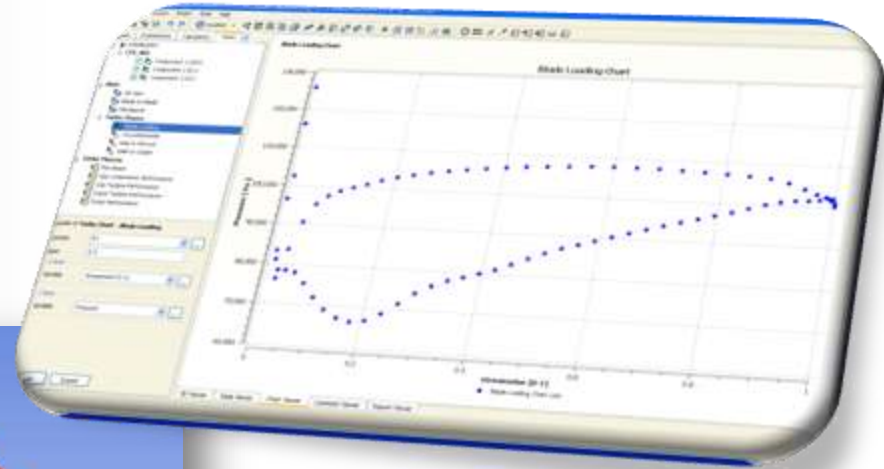
**Phase-shifted boundaries
a consequence of
pitch change**

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

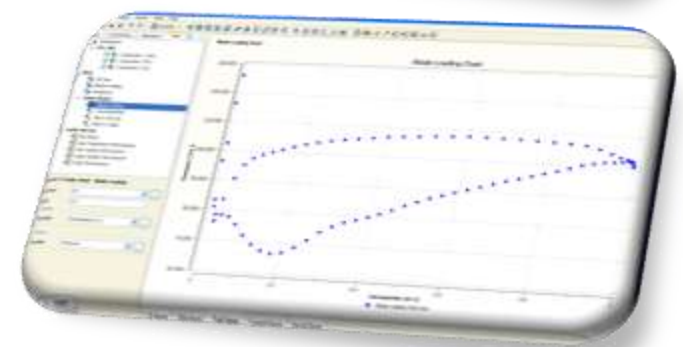
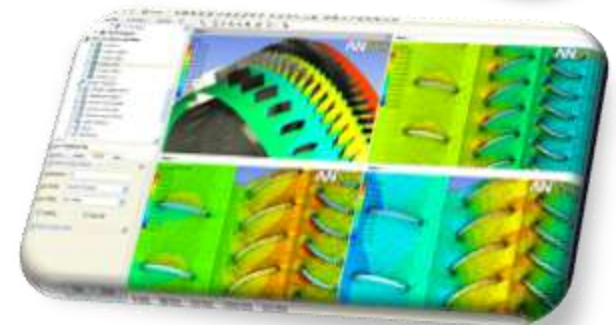
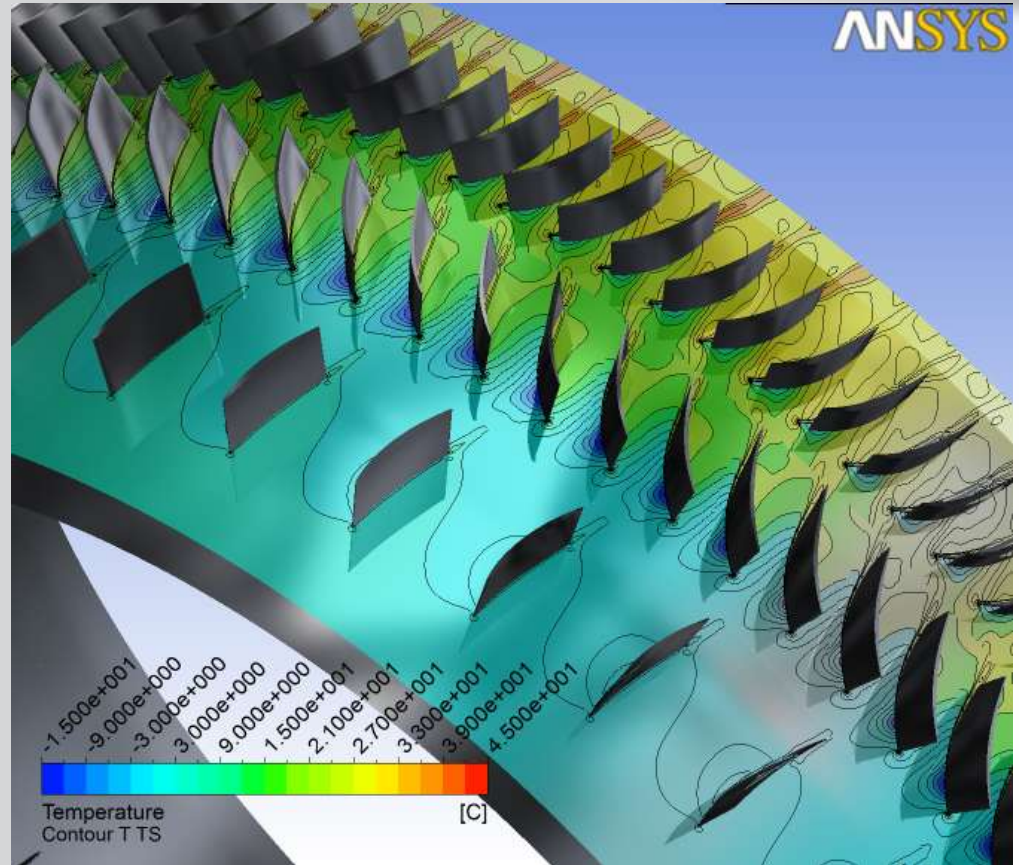
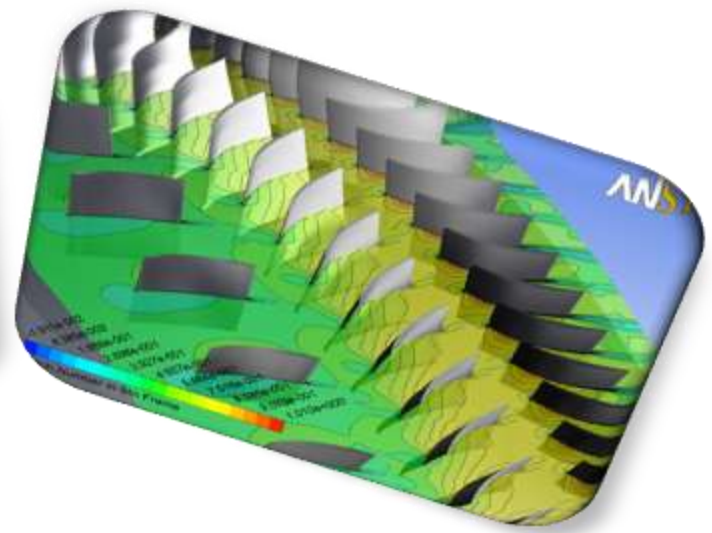
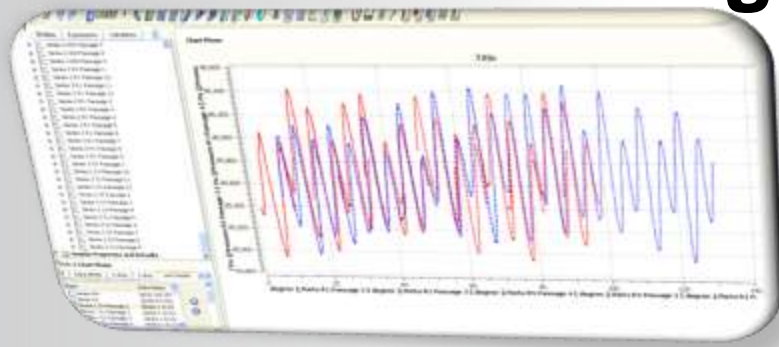


CFD Post-Processing

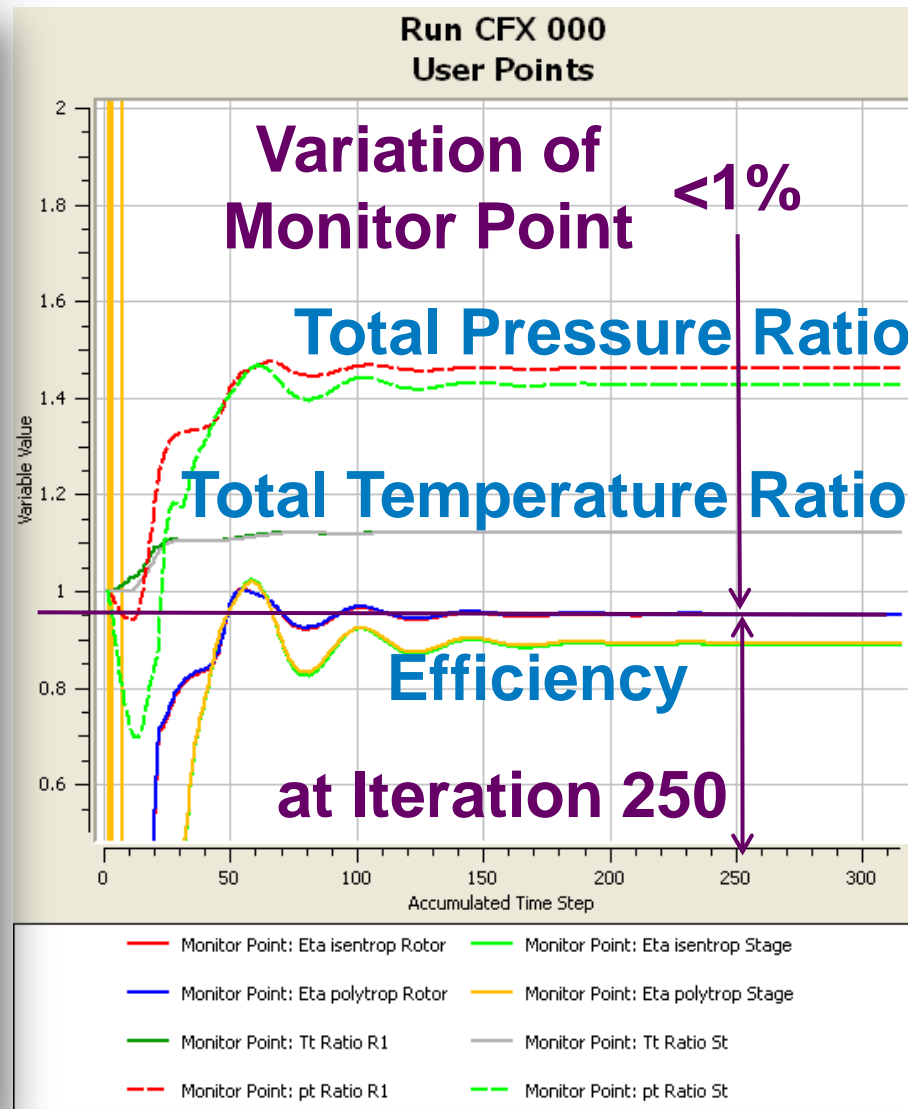
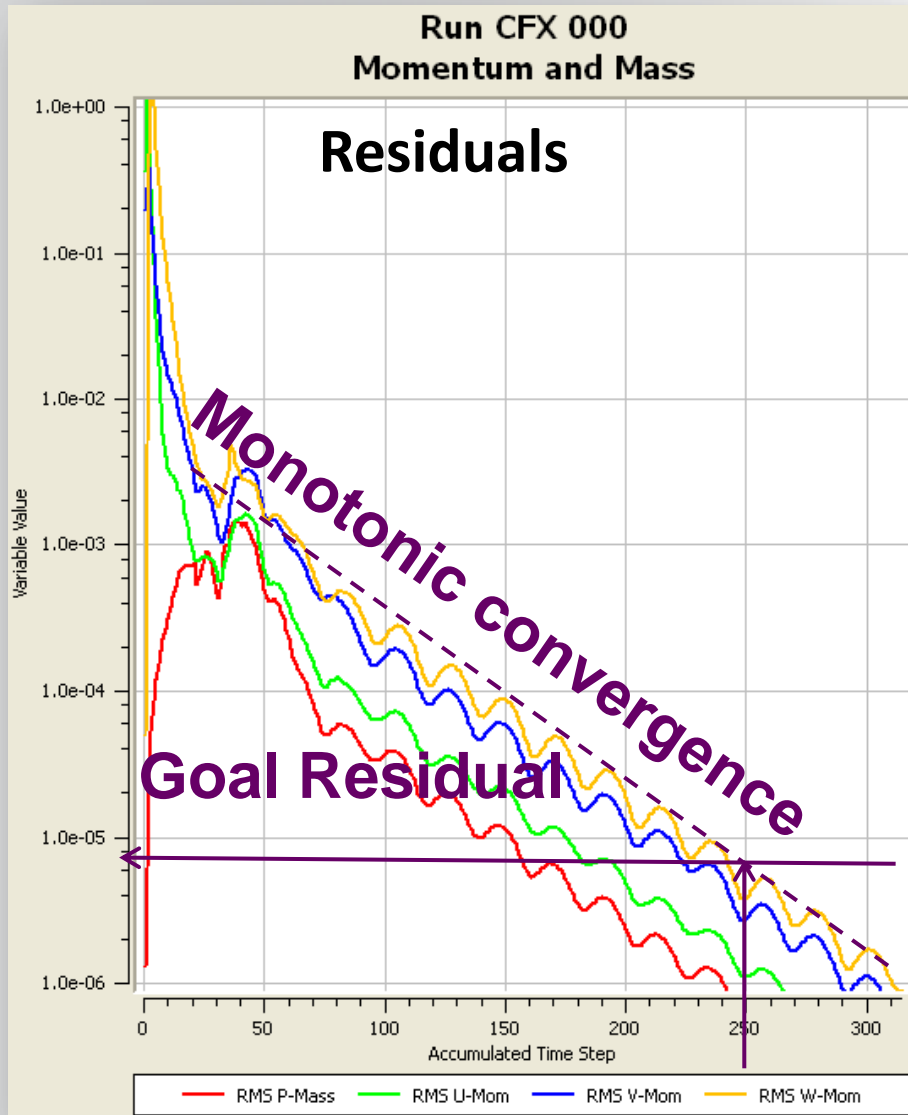
- General Post-Processor
- Turbo Mode
- Highly Automated
- Customizable



CFD Post-Processing

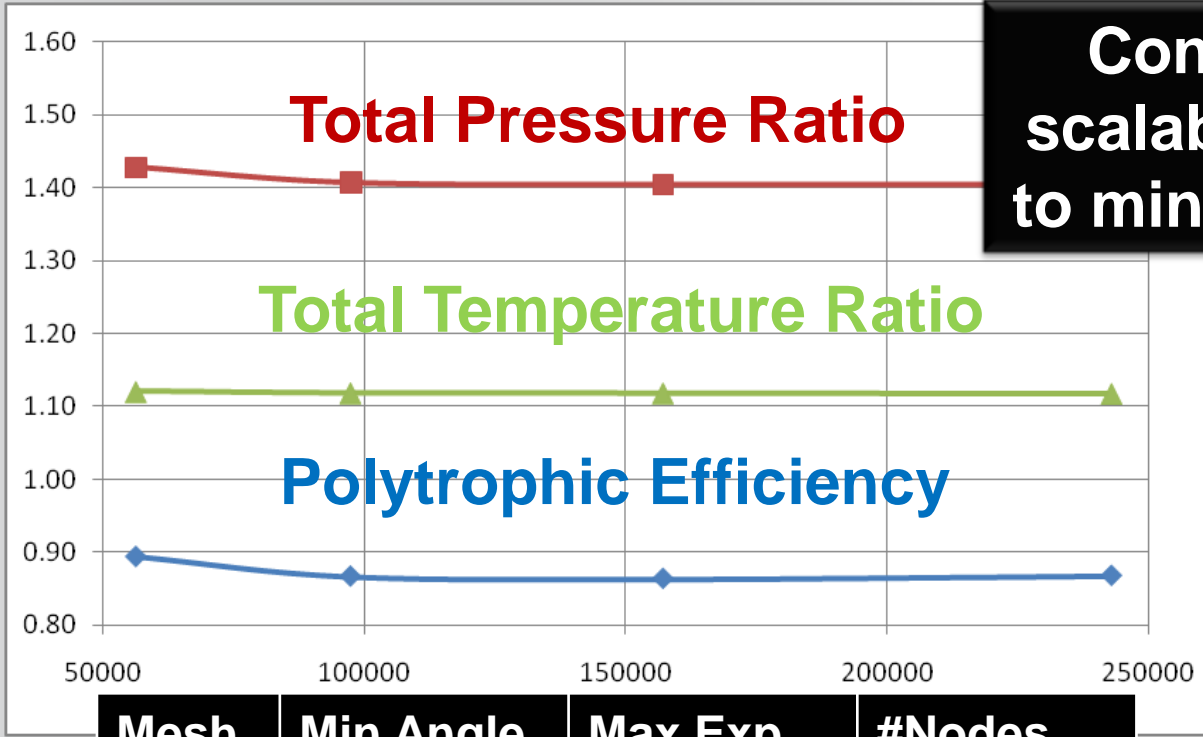


Quality Assurance Iteration Error

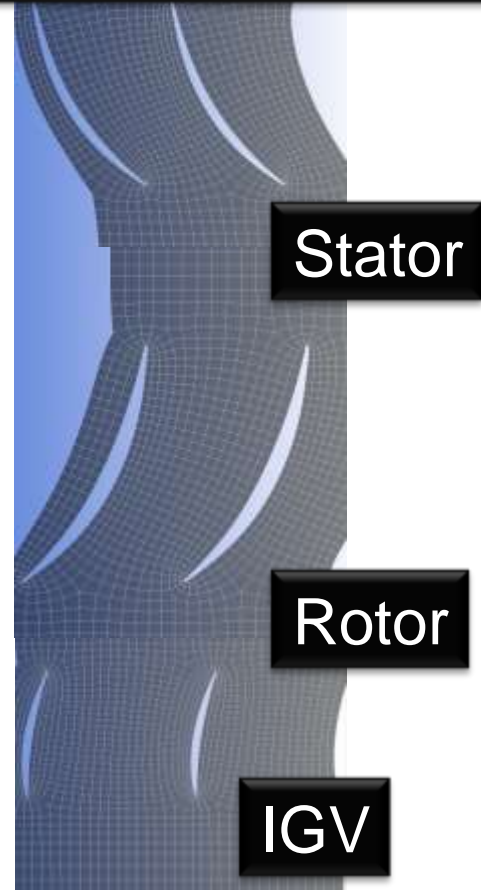


Quality Assurance Discretization Error

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)**

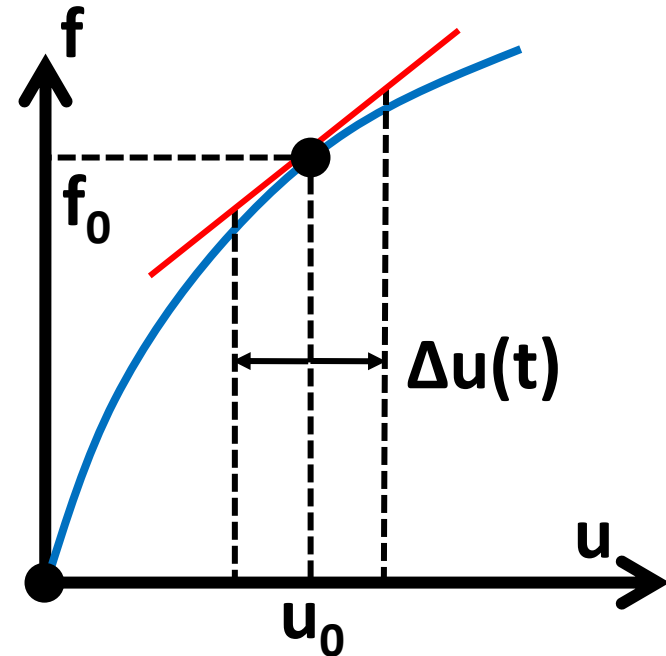
$$K(u_0) \cdot u_0 = f_0$$

- **Modal Analysis**

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

- **Linear dynamic System**

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

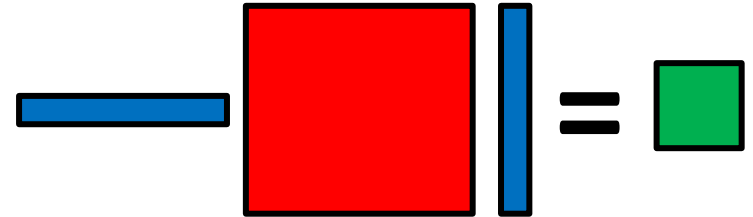


Model Order Reduction

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

- Approximation

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



- leads to reduced dynamic System

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

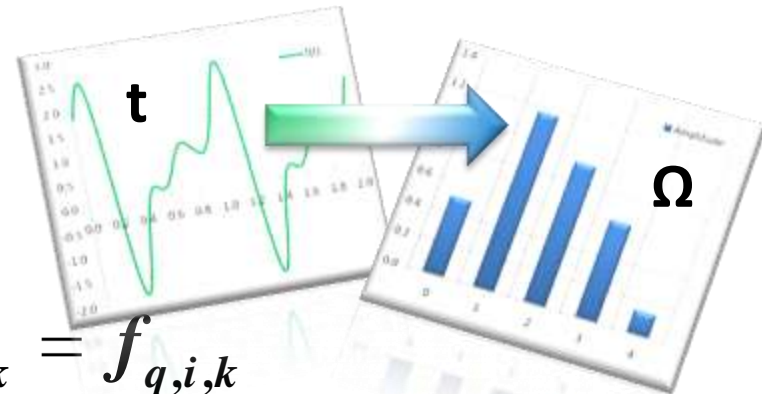
- orthogonality of Φ leads to

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

- Fourier Transformation

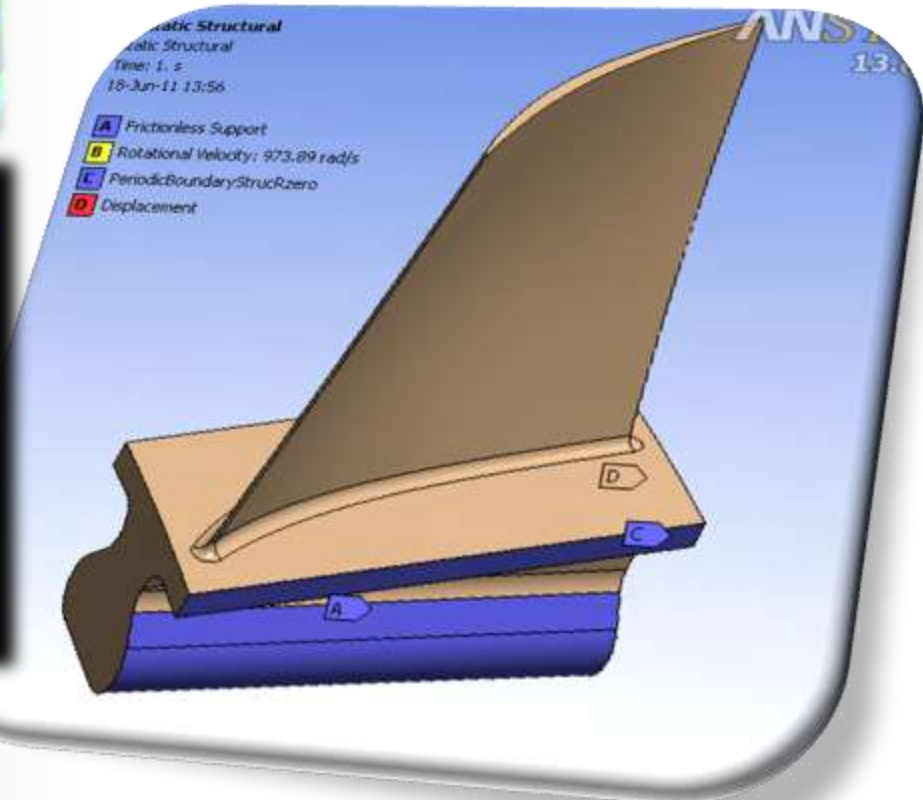
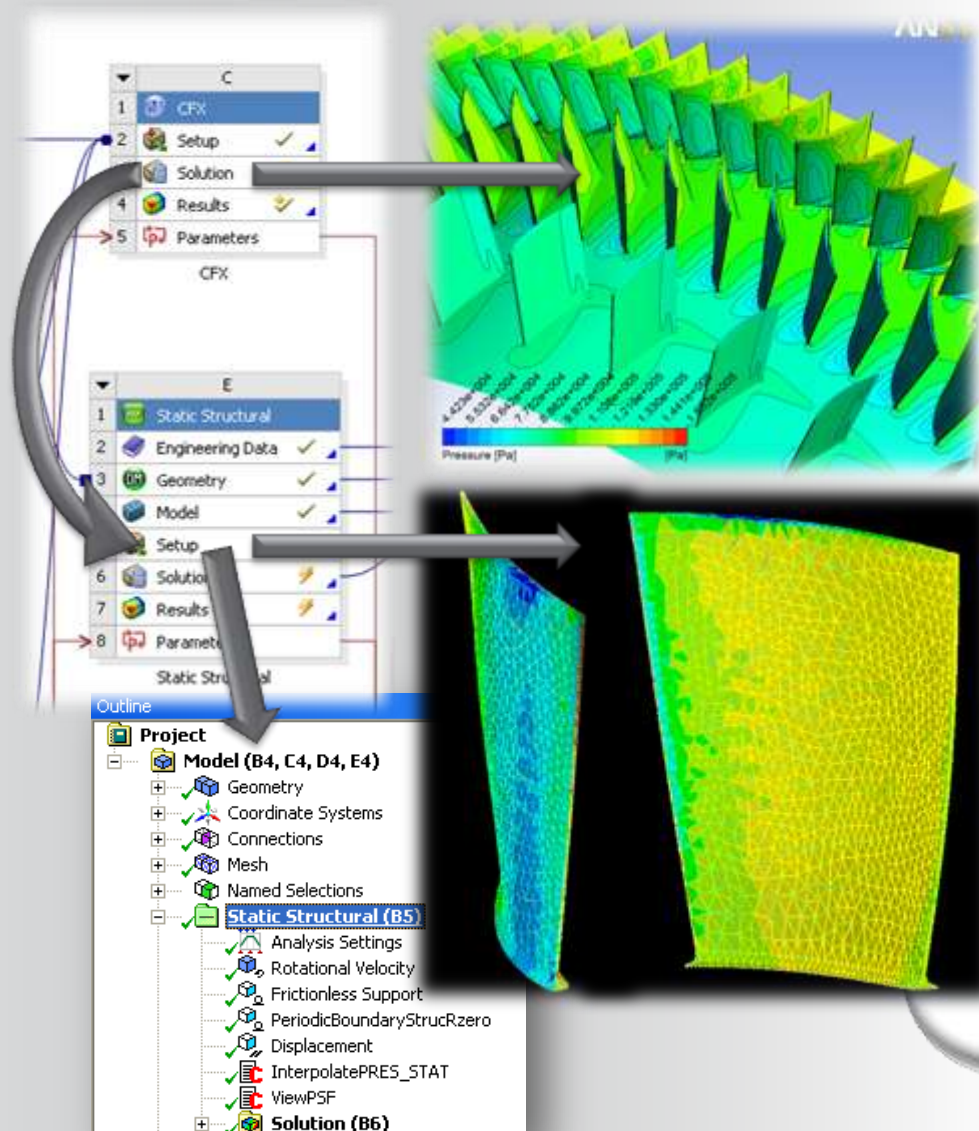
- Time to Frequency Domain

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



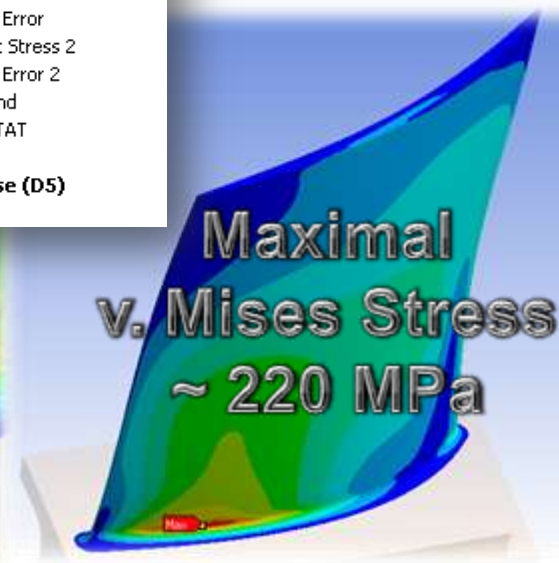
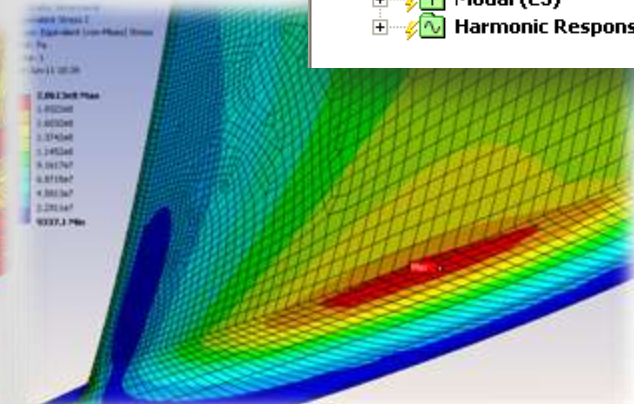
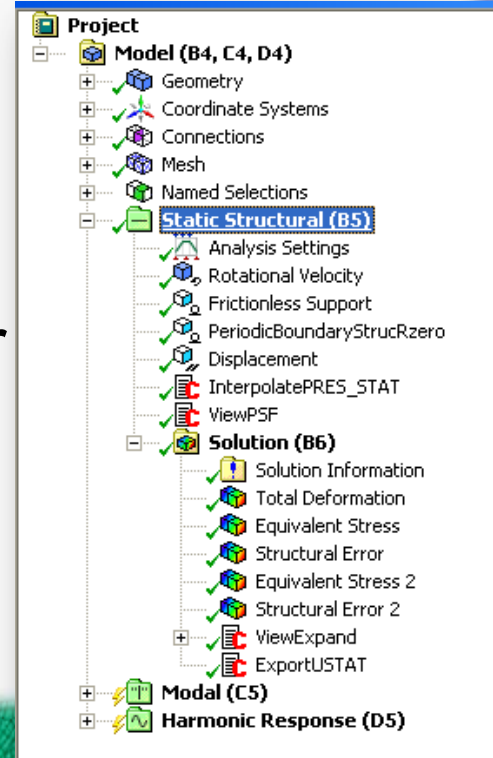
Fluid-Structure Coupling

- Displacements
- Rot. Velocity
- CFD-Pressure



Static Structural (Pre-Stress)

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



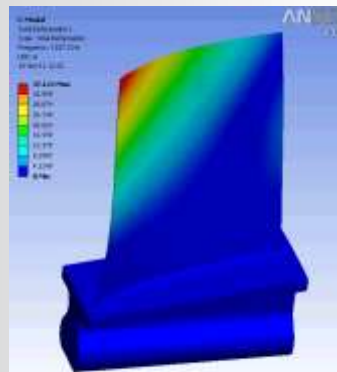
Modal Analysis



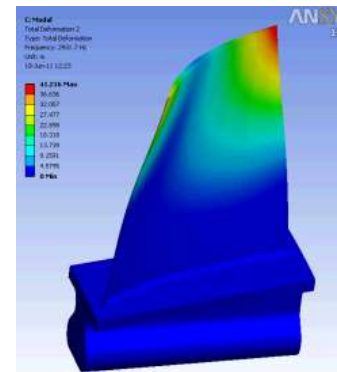
- Pre-Stressed Modal Analysis:
 - Eigen Frequencies and Vectors
 - Data for further MOR-Analysis

	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

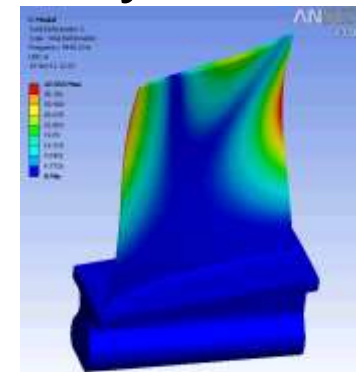
1



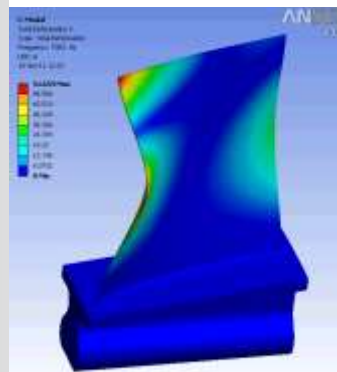
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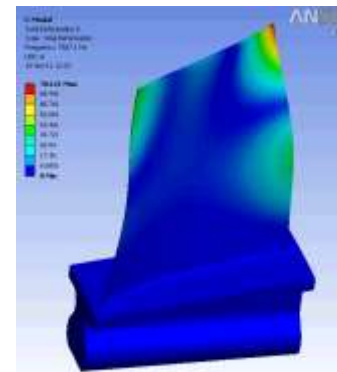
3



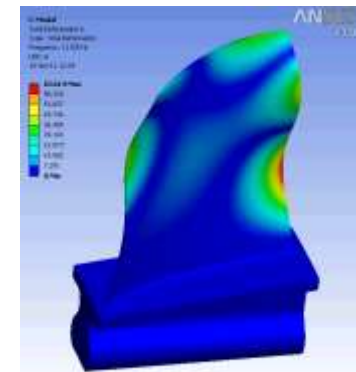
4



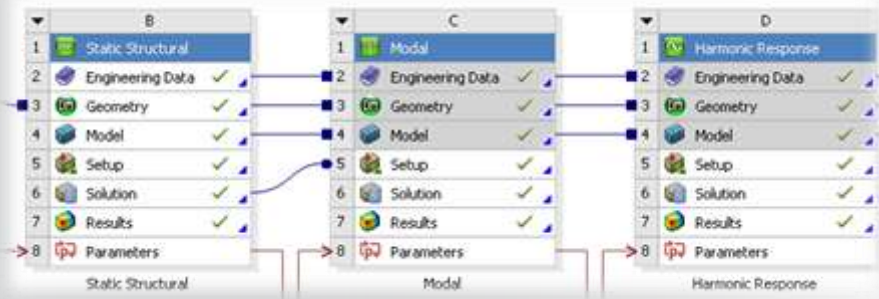
5



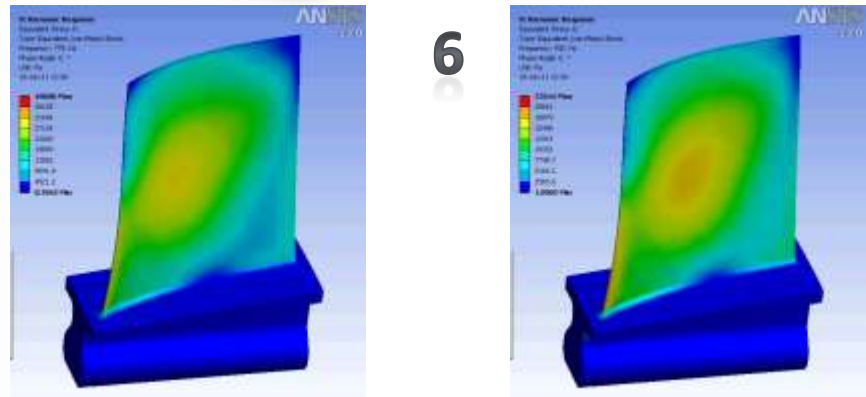
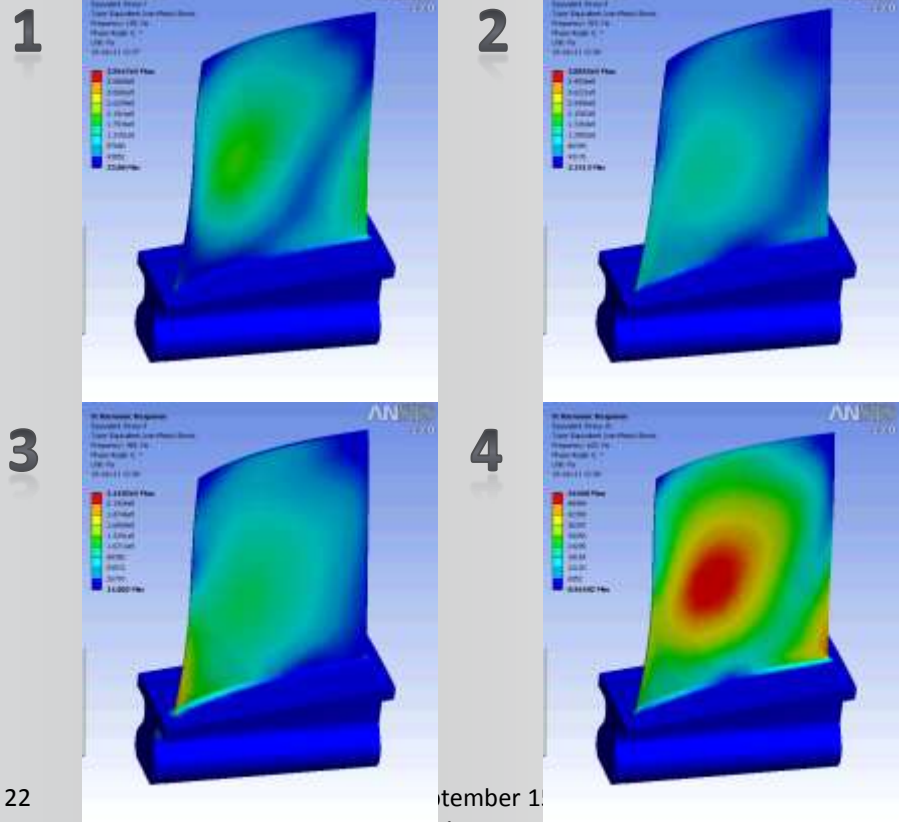
6



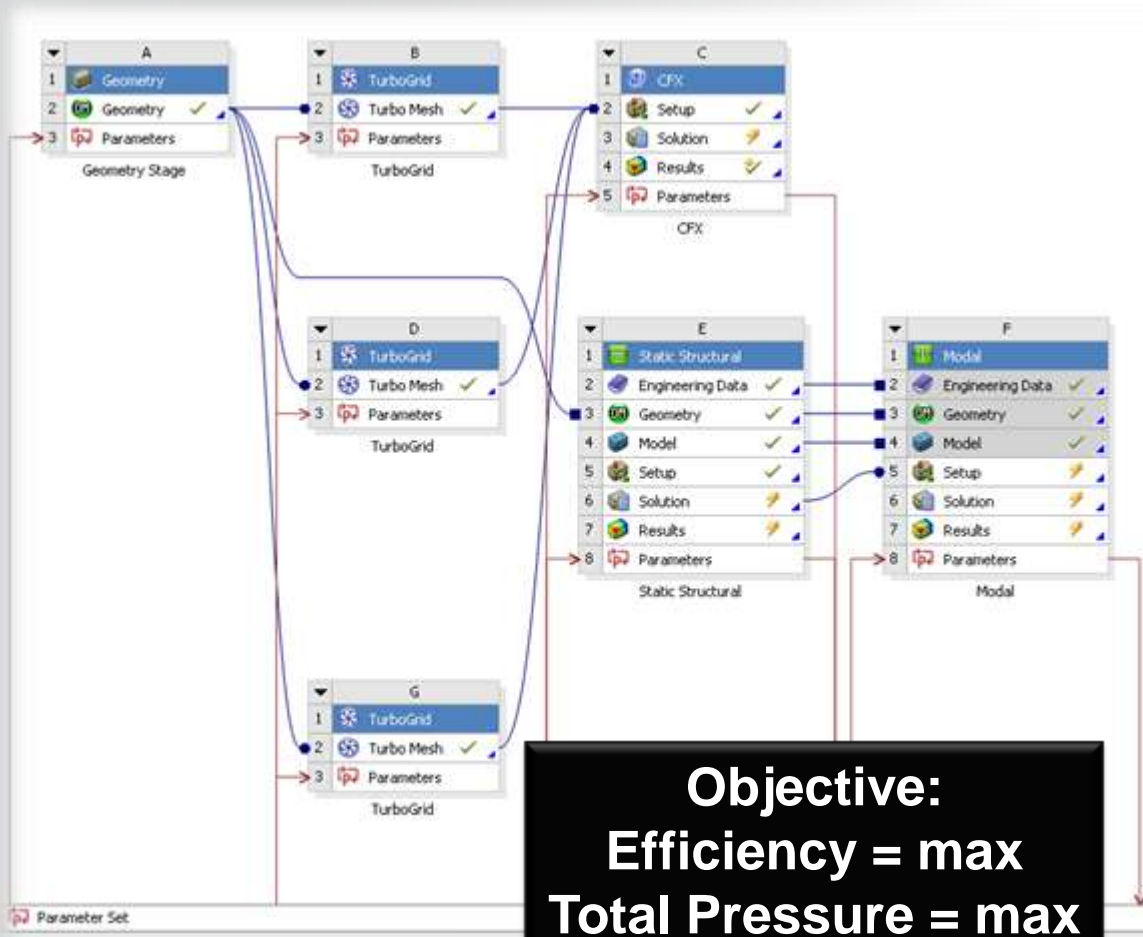
Forced Response Analysis



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



Process Summary and Objectives



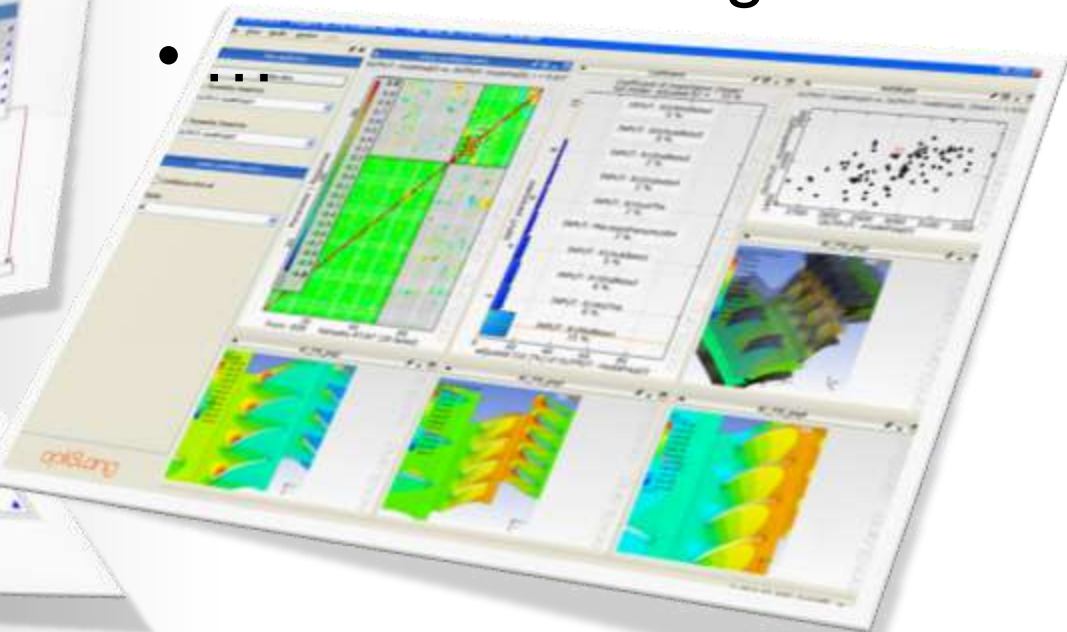
Objective:
Efficiency = max
Total Pressure = max
Stress < Limit
No Resonance

[-] 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	
P22	ptin	
[+] Static Structural (E1)	11 Input Constraints	
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)		24 Output Parameter
New input parameter	New Name	
[+] Output Parameters		
Charts		

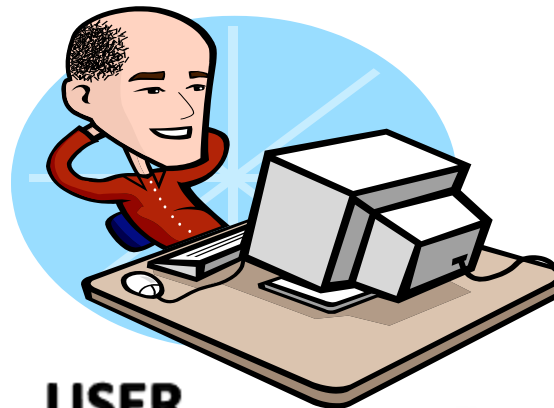
optiSLang Integration/Interface

optiSLang
optimizing structural language

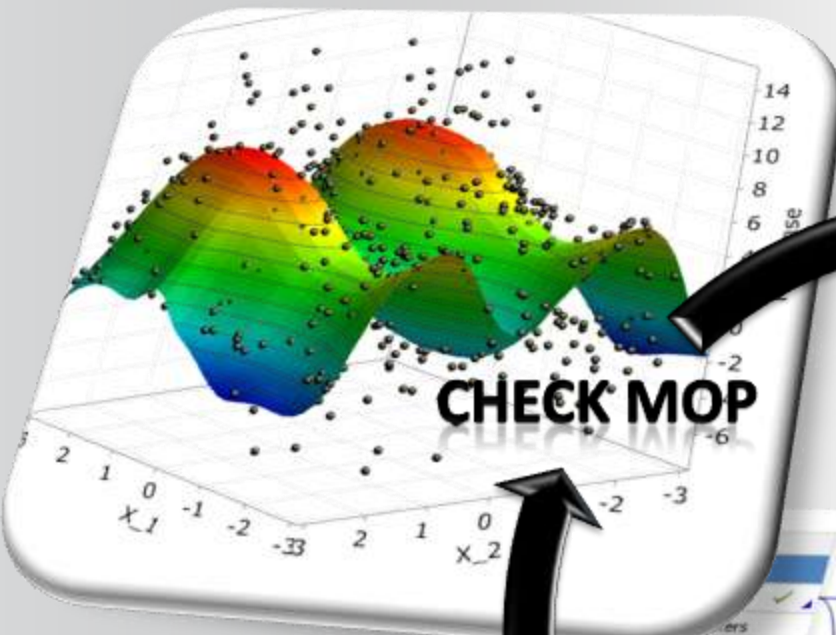
- Direct Integration
- Correlation Matrix
- Coefficient of Prognosis
- 2D and 3D Plot
- Anthill Plot
- Pictures of Design xxxx
- ...



Sensitivity Analysis

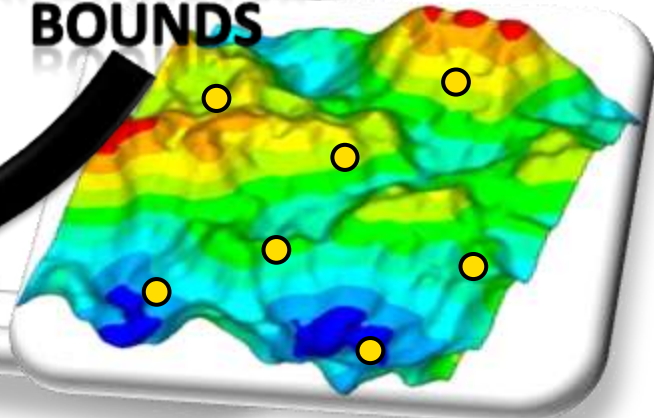


USER INTERACTION

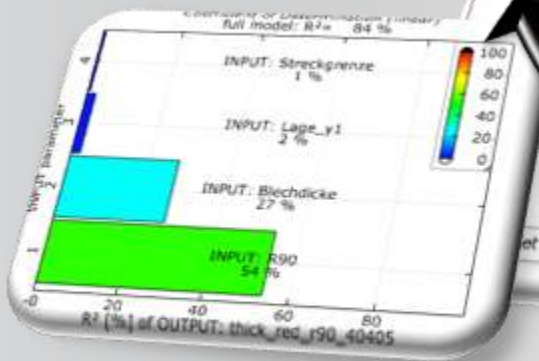


Parameter	Value
Pressure	83.3
ExitVel	26.2
FlowRate	206.3
HubVel1	-46.4
HubVel2	-25.6
HubVel3	-25.6
HubVel4	-26.7
HubVel5	-26.7
HubVel6	-26.7
HubVel7	-26.7
HubVel8	-26.7
HubVel9	-26.7
HubVel10	-26.7
HubVel11	-26.7
HubVel12	-26.7
HubVel13	-26.7
HubVel14	-26.7
HubVel15	-26.7
HubVel16	-26.7
HubVel17	-26.7
HubVel18	-26.7
HubVel19	-26.7
HubVel20	-26.7
HubVel21	-26.7
HubVel22	-26.7
HubVel23	-26.7
HubVel24	-26.7
HubVel25	-26.7
HubVel26	-26.7
HubVel27	-26.7
HubVel28	-26.7
HubVel29	-26.7
HubVel30	-26.7
HubVel31	-26.7
HubVel32	-26.7
HubVel33	-26.7
HubVel34	-26.7
HubVel35	-26.7
HubVel36	-26.7
HubVel37	-26.7
HubVel38	-26.7
HubVel39	-26.7
HubVel40	-26.7
HubVel41	-26.7
HubVel42	-26.7
HubVel43	-26.7
HubVel44	-26.7
HubVel45	-26.7
HubVel46	-26.7
HubVel47	-26.7
HubVel48	-26.7
HubVel49	-26.7
HubVel50	-26.7
HubVel51	-26.7
HubVel52	-26.7
HubVel53	-26.7
HubVel54	-26.7
HubVel55	-26.7
HubVel56	-26.7
HubVel57	-26.7
HubVel58	-26.7
HubVel59	-26.7
HubVel60	-26.7
HubVel61	-26.7
HubVel62	-26.7
HubVel63	-26.7
HubVel64	-26.7
HubVel65	-26.7
HubVel66	-26.7
HubVel67	-26.7
HubVel68	-26.7
HubVel69	-26.7
HubVel70	-26.7
HubVel71	-26.7
HubVel72	-26.7
HubVel73	-26.7
HubVel74	-26.7
HubVel75	-26.7
HubVel76	-26.7
HubVel77	-26.7
HubVel78	-26.7
HubVel79	-26.7
HubVel80	-26.7
HubVel81	-26.7
HubVel82	-26.7
HubVel83	-26.7
HubVel84	-26.7
HubVel85	-26.7
HubVel86	-26.7
HubVel87	-26.7
HubVel88	-26.7
HubVel89	-26.7
HubVel90	-26.7
HubVel91	-26.7
HubVel92	-26.7
HubVel93	-26.7
HubVel94	-26.7
HubVel95	-26.7
HubVel96	-26.7
HubVel97	-26.7
HubVel98	-26.7
HubVel99	-26.7
HubVel100	-26.7

PARAMETER BOUNDS

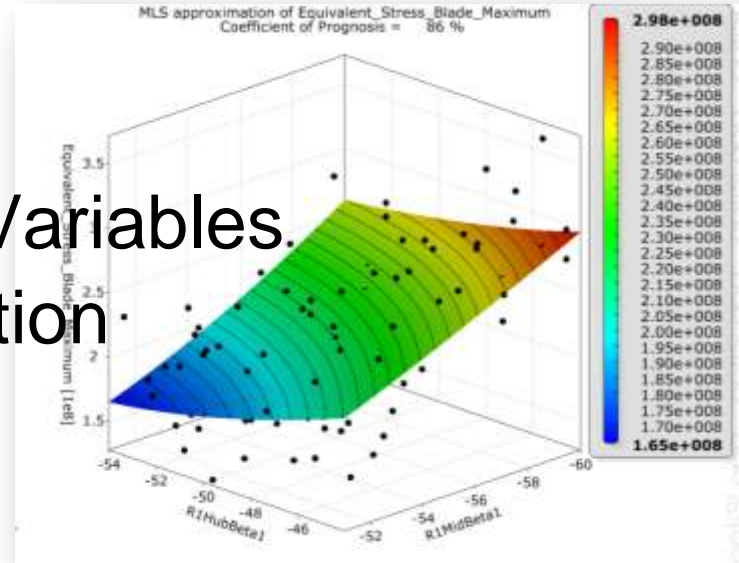
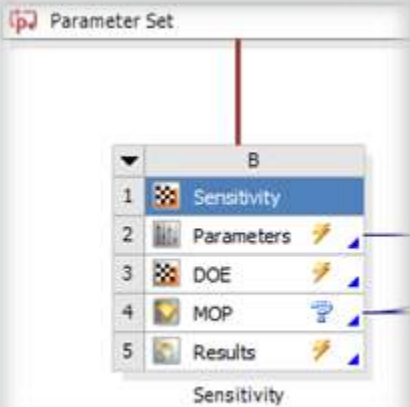


LHS-SAMPLING

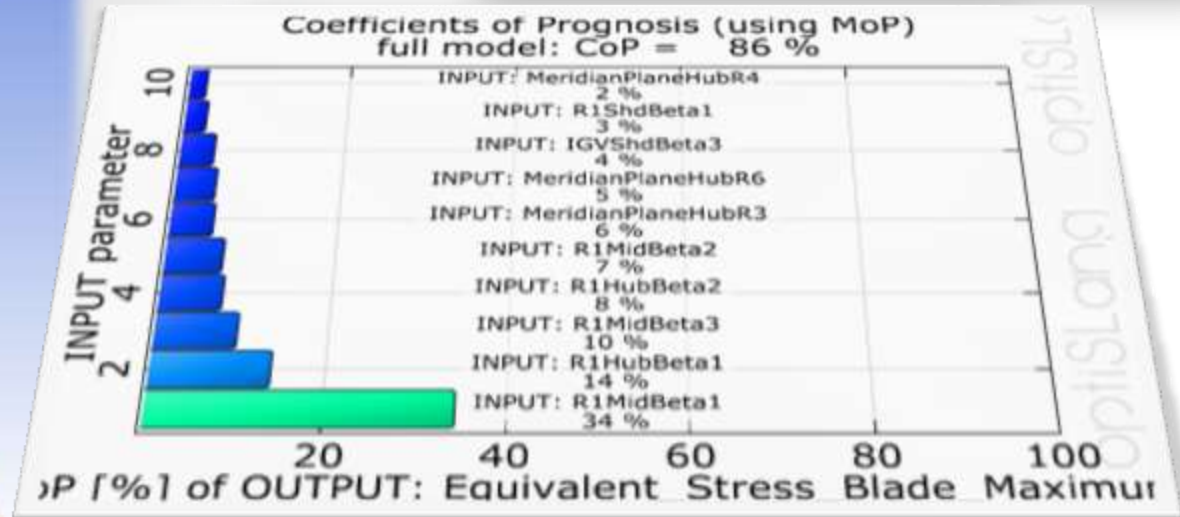
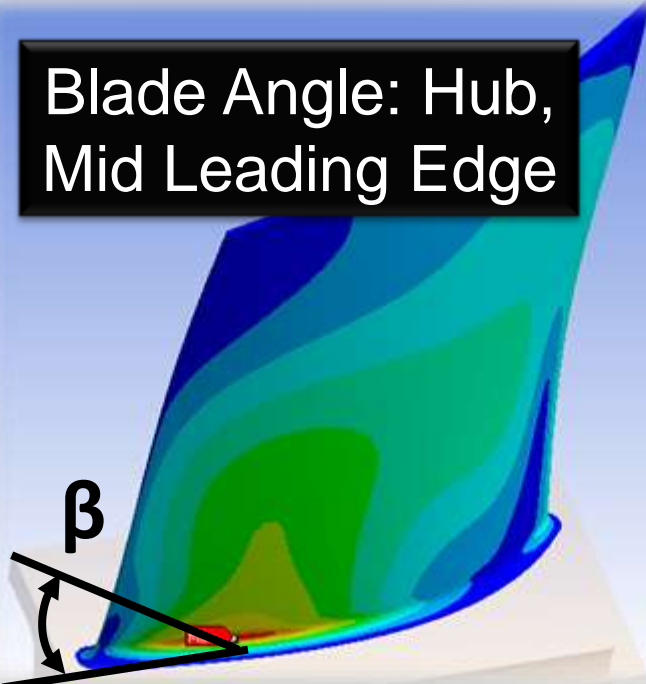


Sensitivity Analysis, Maximal Stress

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

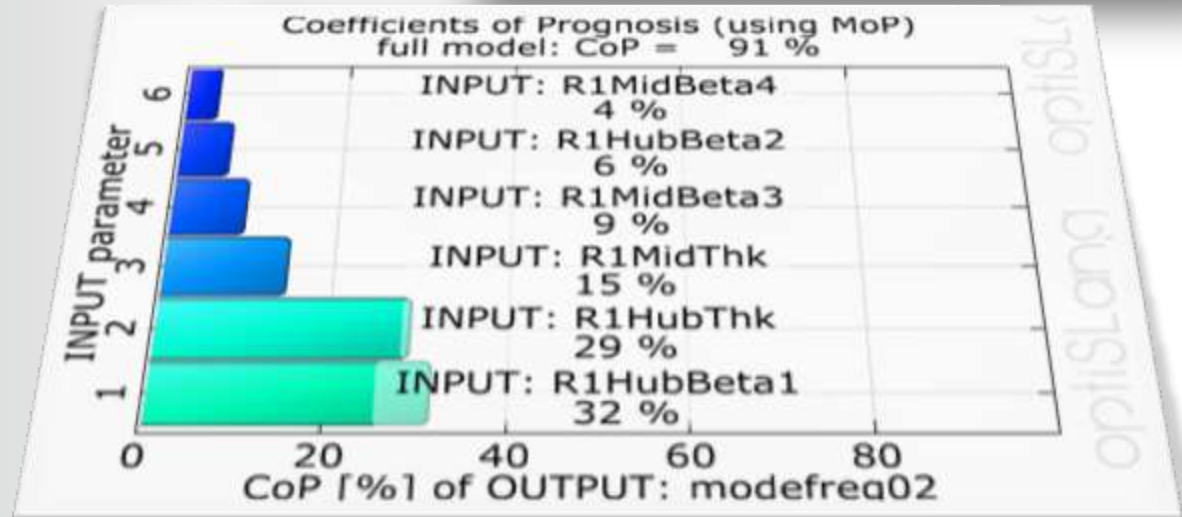
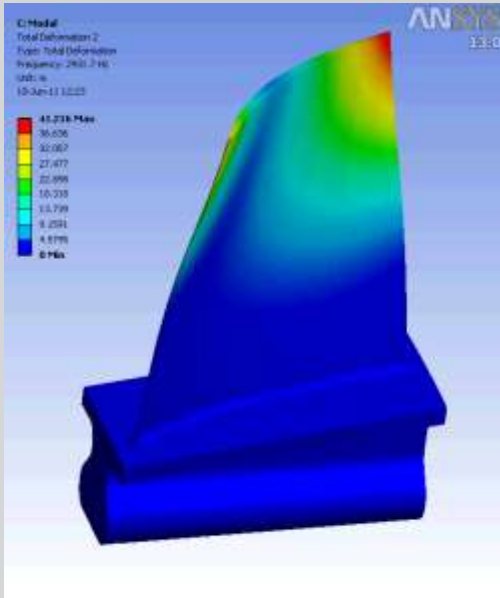
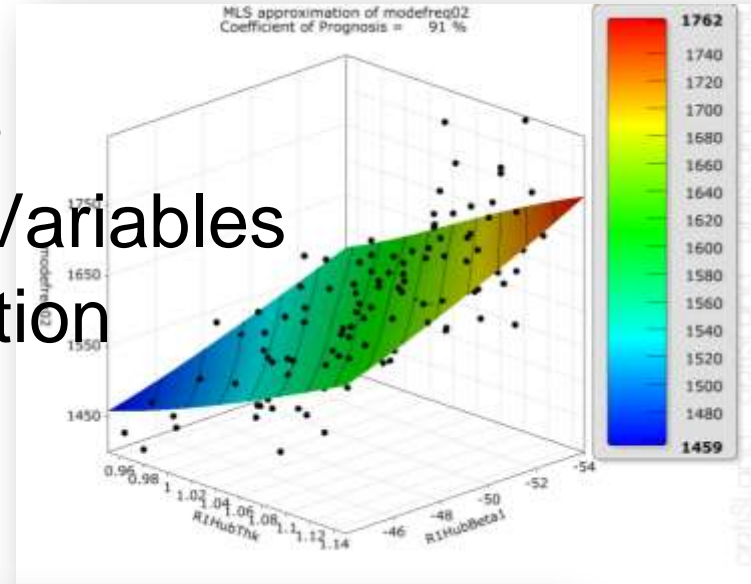
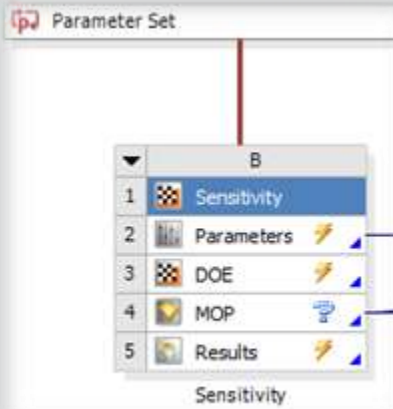


Blade Angle: Hub, Mid Leading Edge

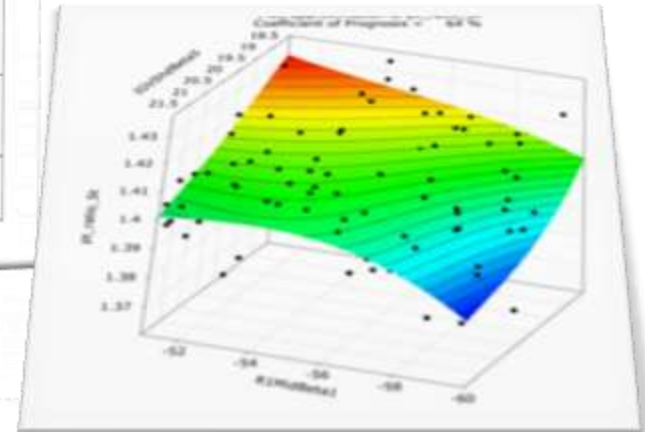
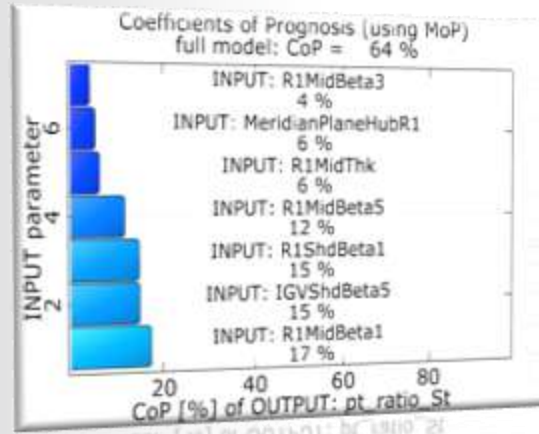
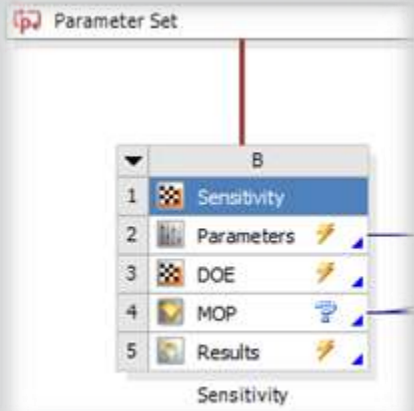


Sensitivity Analysis, Eigen Mode 2

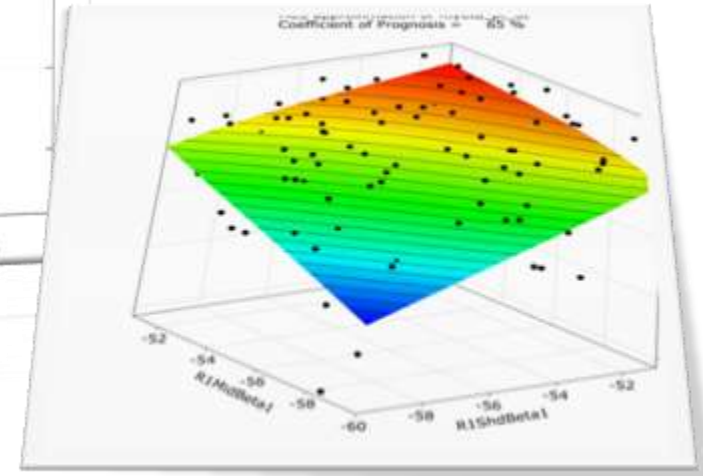
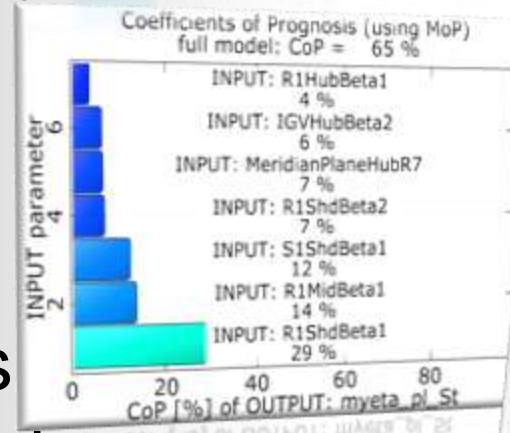
- CoP=91%
 - Statistic is reliable
 - Detect important Variables
 - Parameter Reduction
- MoP is plausible



Sensitivity Analysis, Aero Dynamic

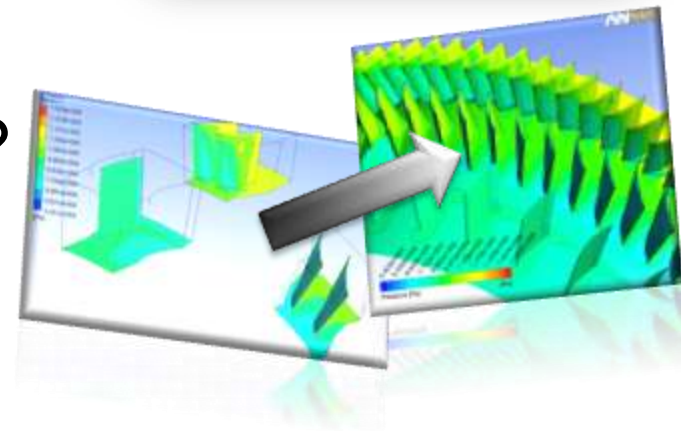
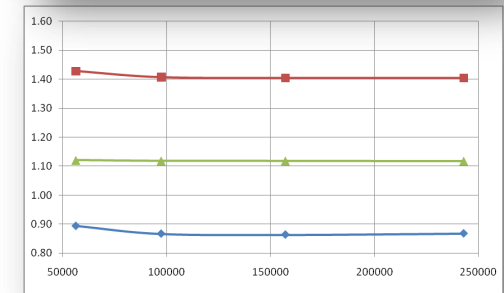
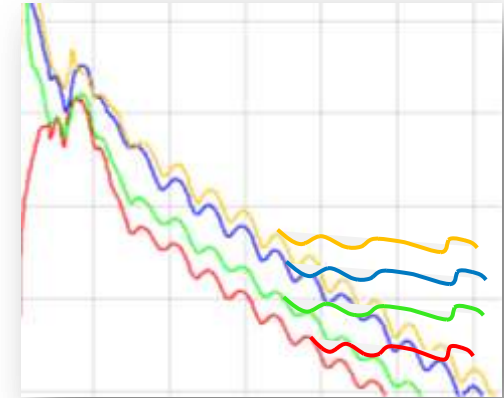


- CoP=64% and 65%
 - small value
 - Numerical error?
 - Model error?
- Important Variables
 - Parameter Reduction
- MoP is plausible



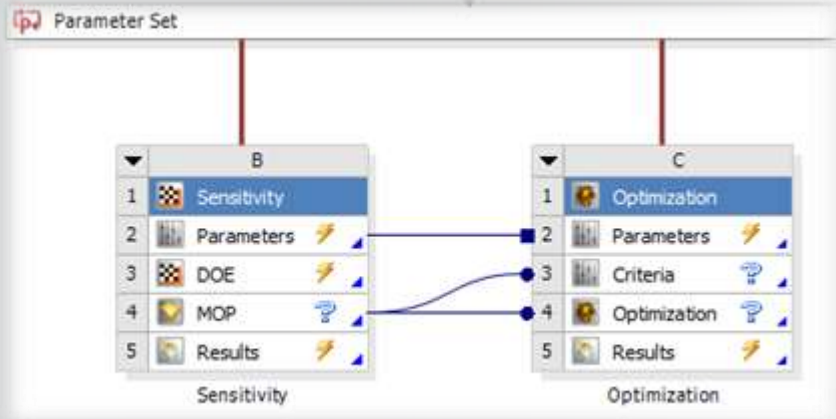
Trouble Shooting with small CoP

- 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:



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

Which one is the best?

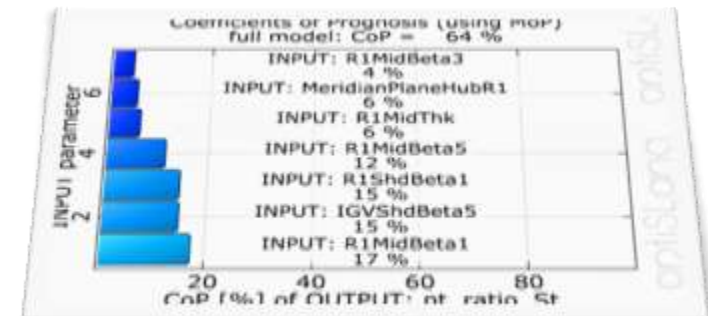
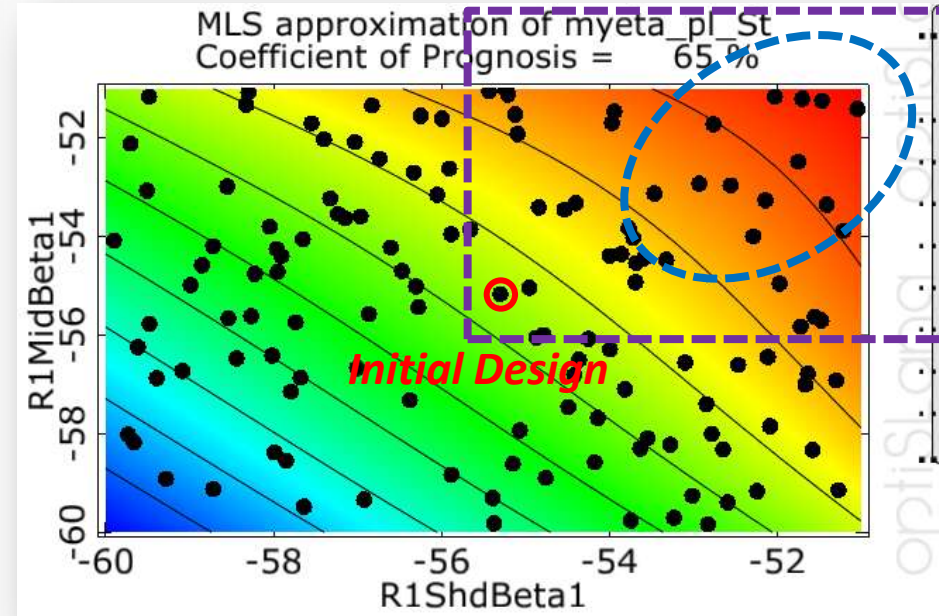
- Evolutionary Algorithm
- Gradient-Based Algorithms
- Pareto Optimization
- Adaptive Response Surface
- Generic Algorithm

Sensitivity Analysis:

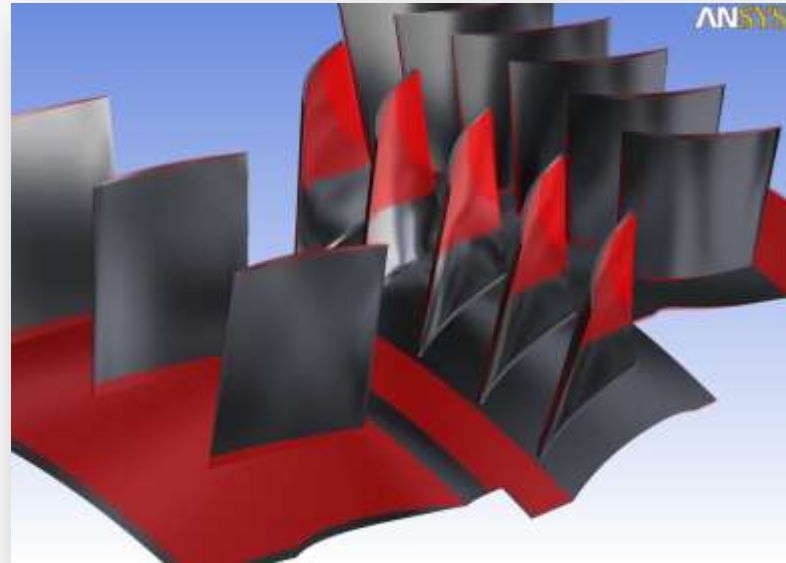
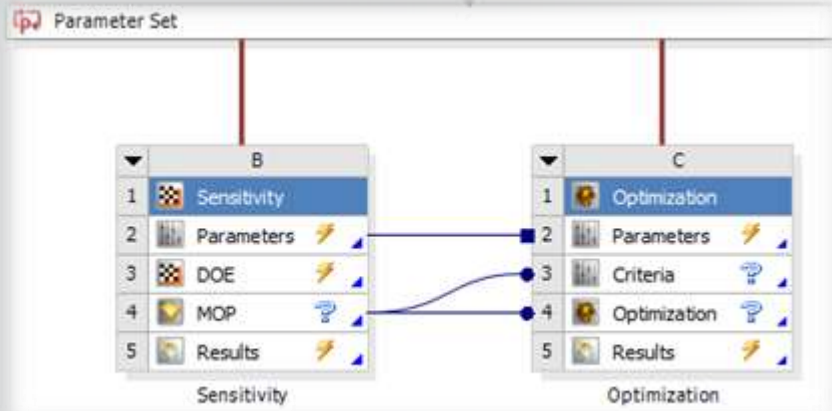
- Shows potential
- Indicates global optimum
- Parameter reduction
- Modify parameter space

Strategy:

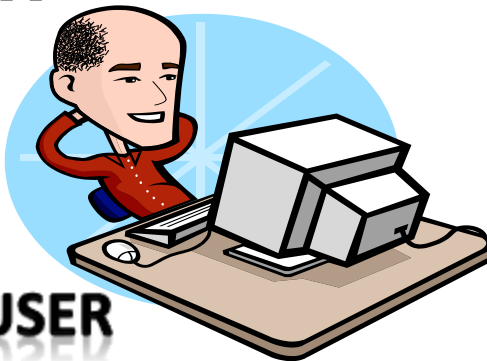
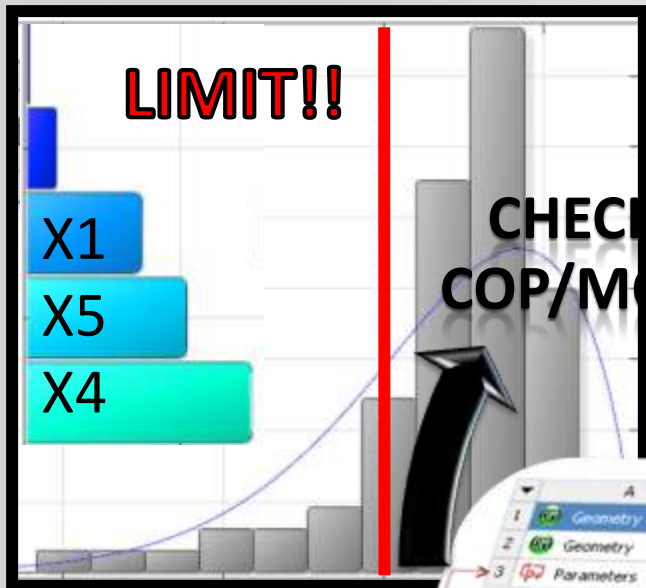
- Get best Design from SA/MoP
- Evaluate this Design and get initial for:
- Optimization in sub space: ARSM
 - Small Number of Parameter
 - Global Optimum



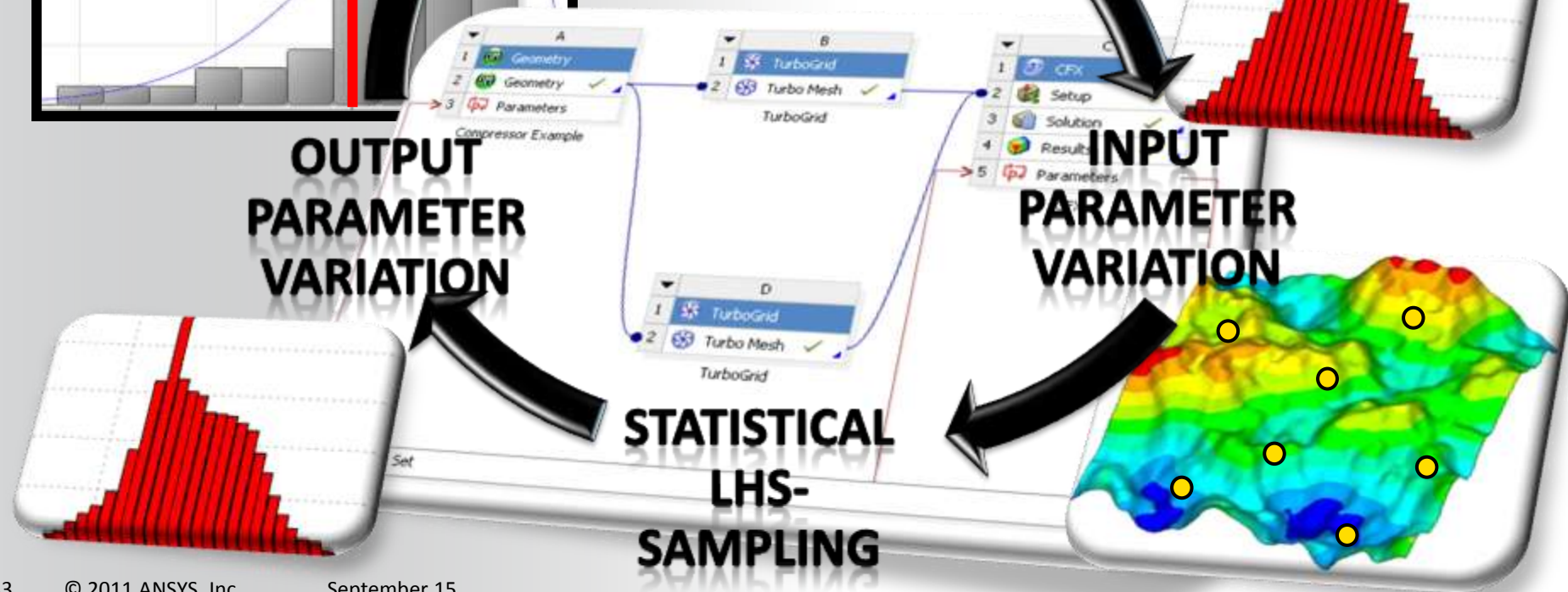
Design Optimization, Summary



	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



USER INTERACTION

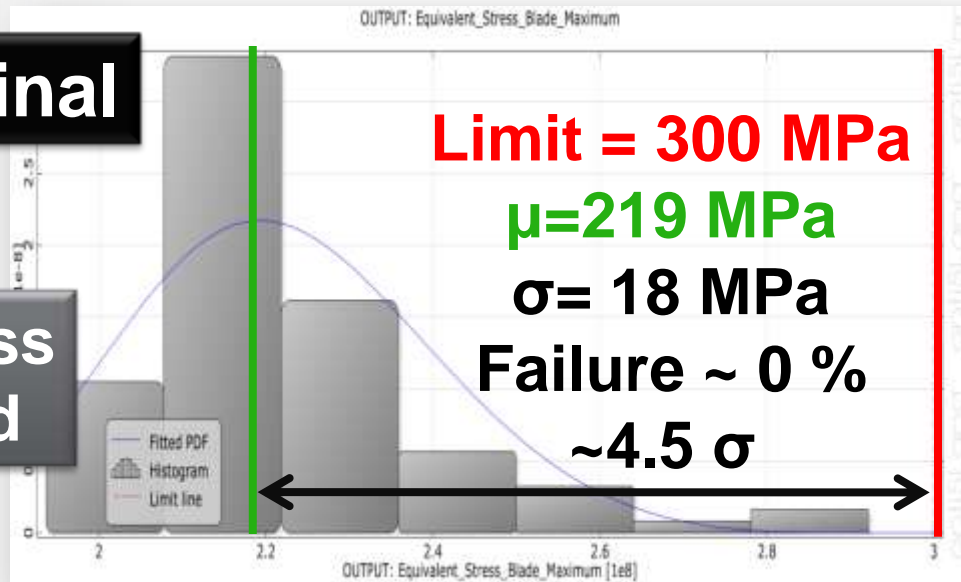


Robustness, Maximum Stress

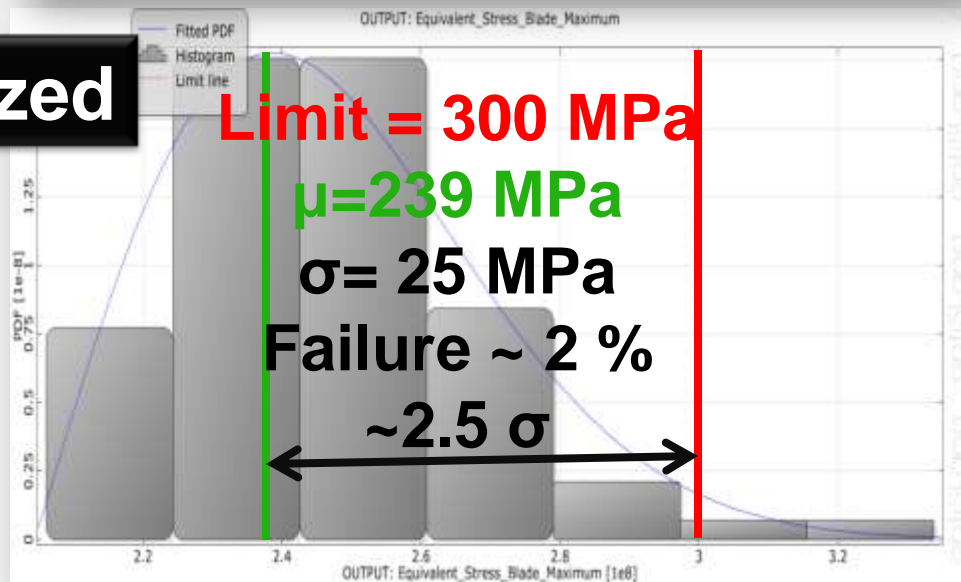
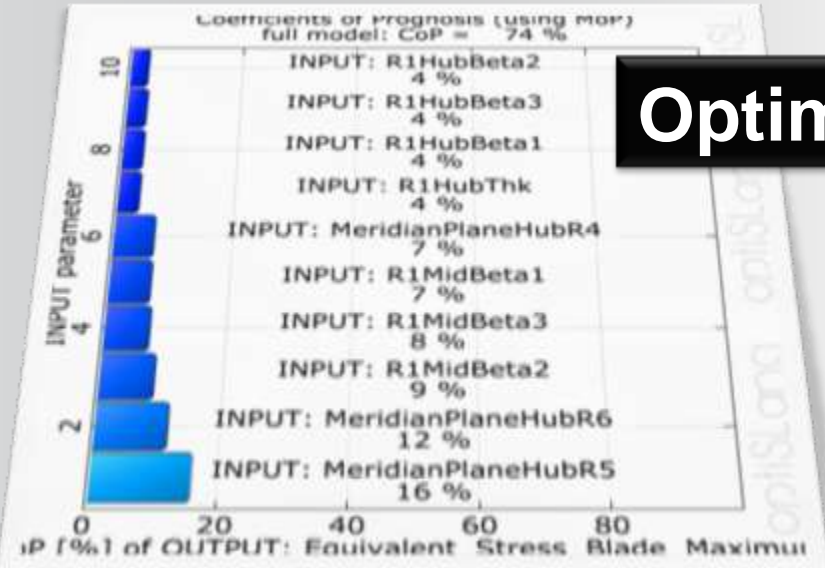


Original

Robustness decreased



Optimized

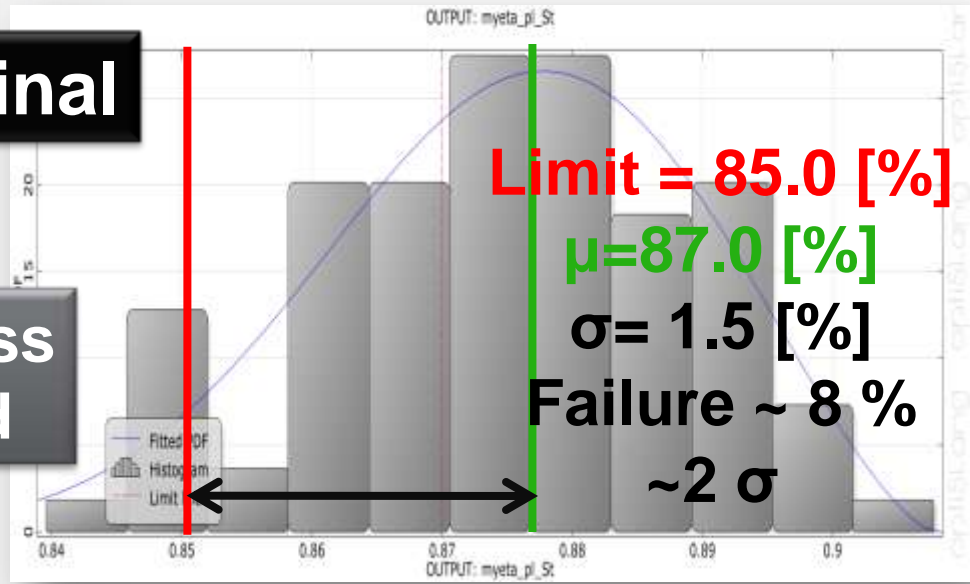


Robustness, Efficiency

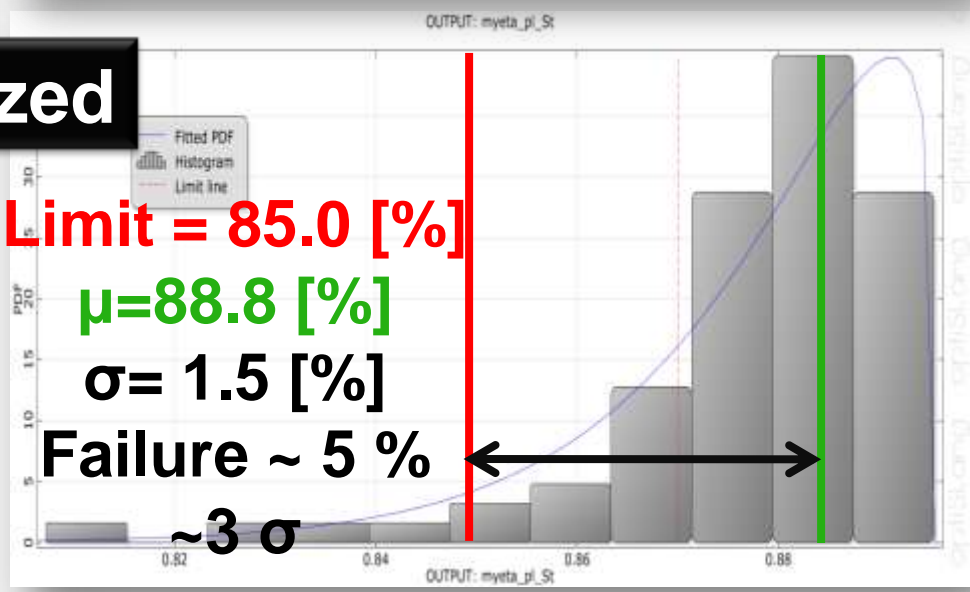
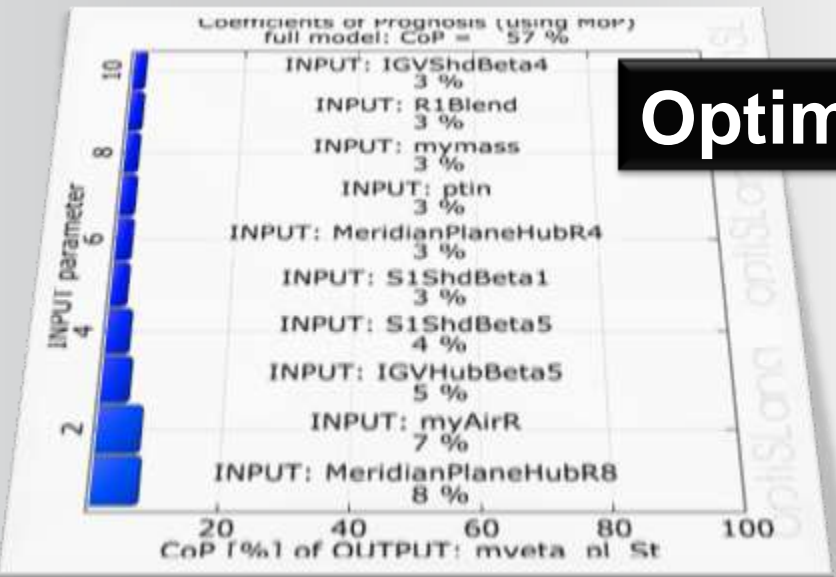


Original

Robustness increased



Optimized



Robustness, Total Pressure Ratio

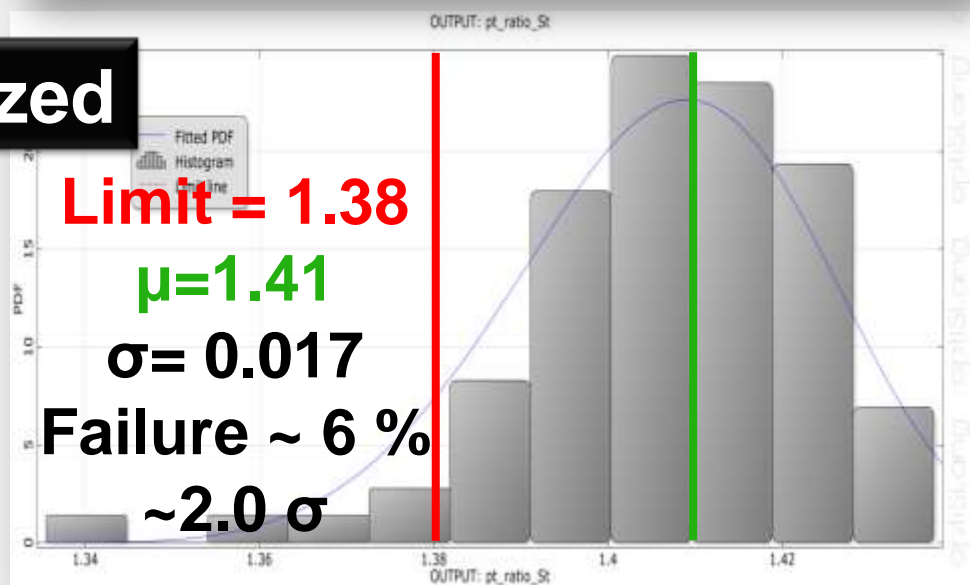
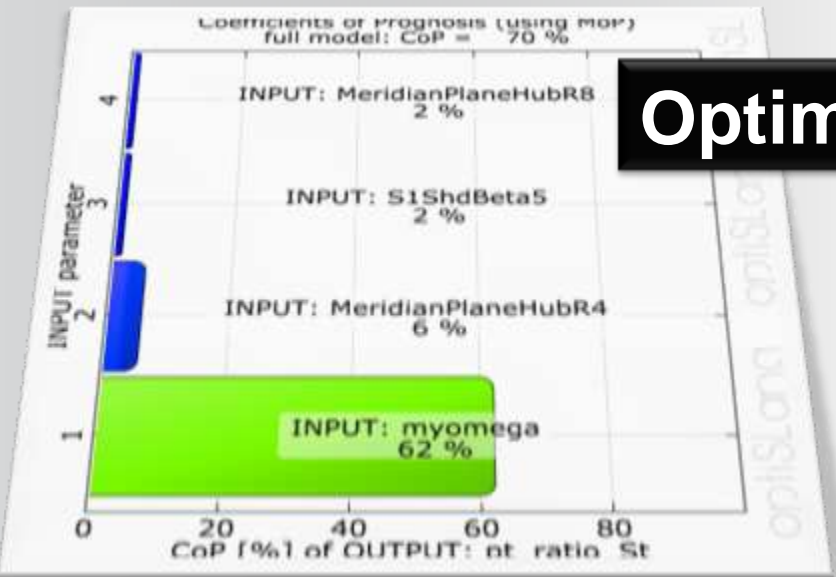


Original

Robustness approx. equal



Optimized



Summary

optiSLang
 optimizing structural language

**AUTOMATIZATION
 OPTIMIZATION**

**MULTIPHYSICS
 COUPLING**

**BREADTH
 DEPTH**

