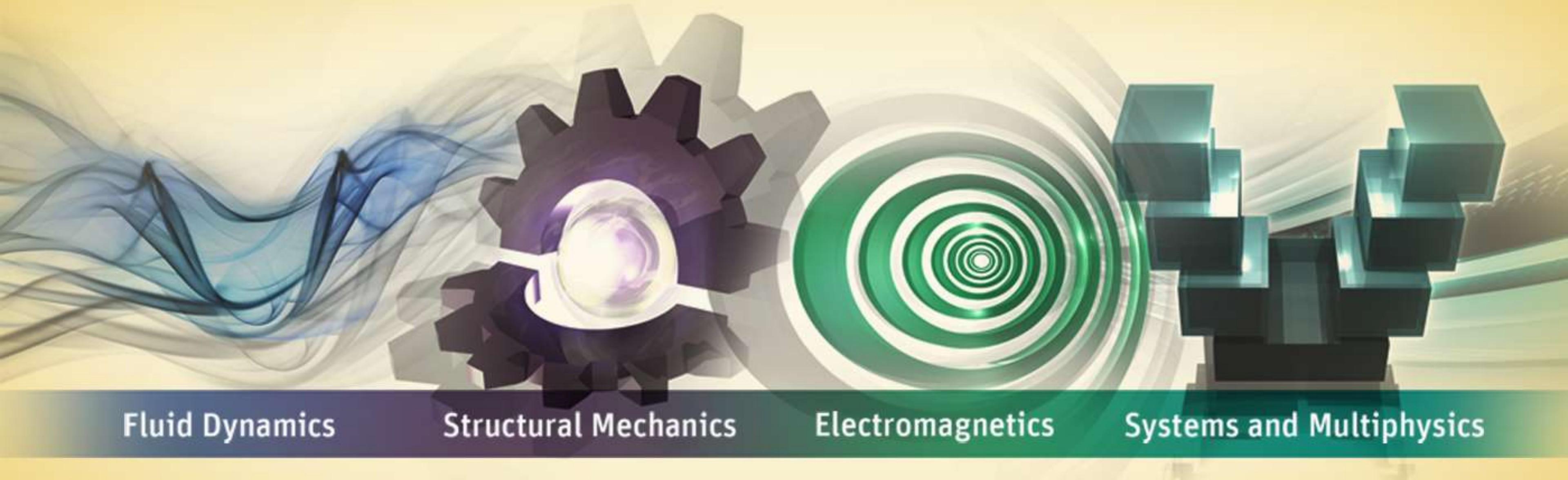
Robust Design Optimization of an Axial Compressor

Realize Your Product Promise™

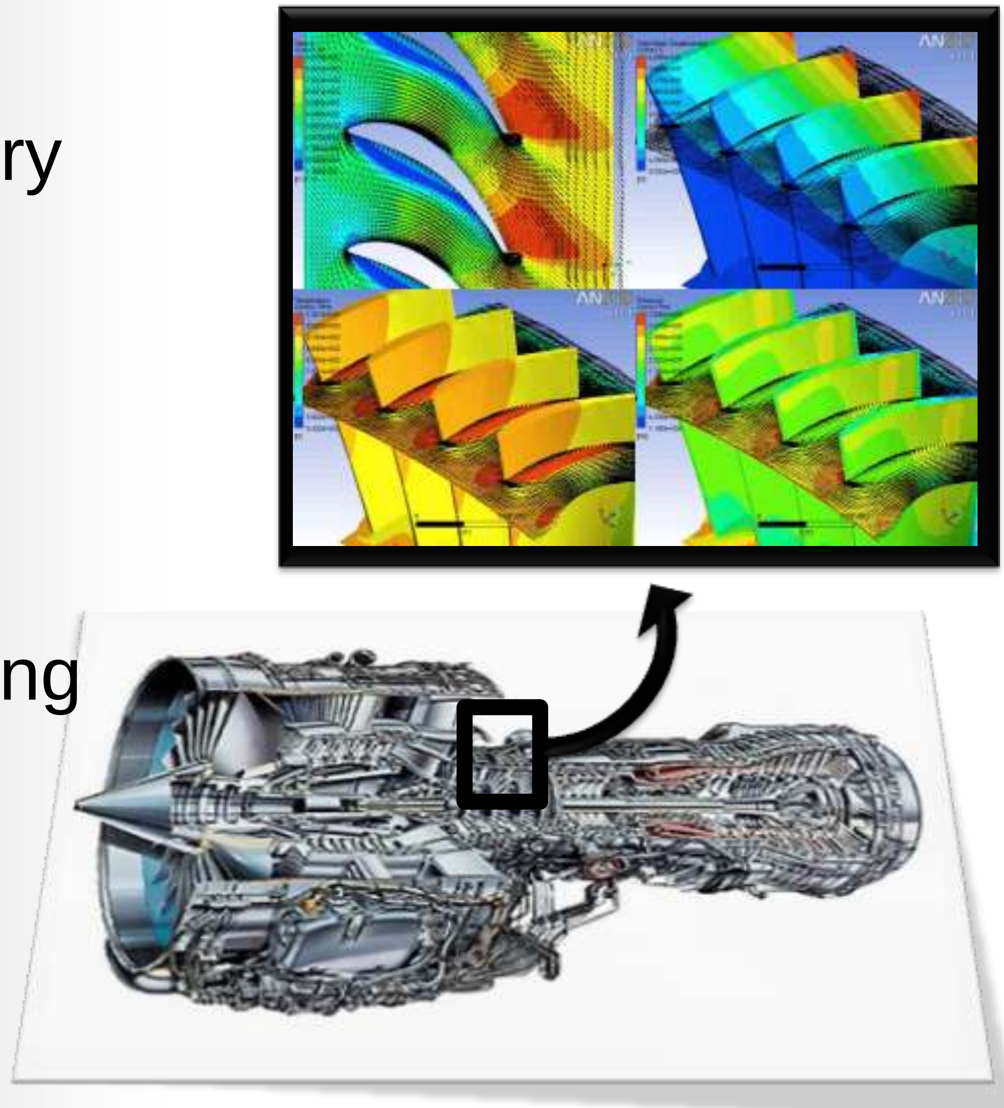


Johannes Einzinger
ANSYS Germany GmbH

Motivation

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

High Requirement for Optimization



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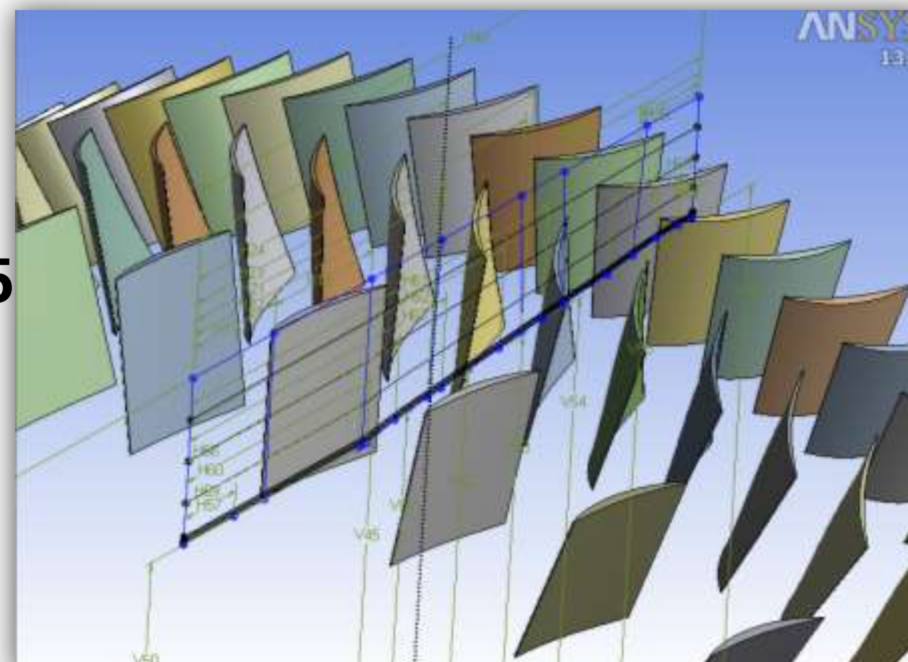
Primary Design, PCA Engineers

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



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Outline

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

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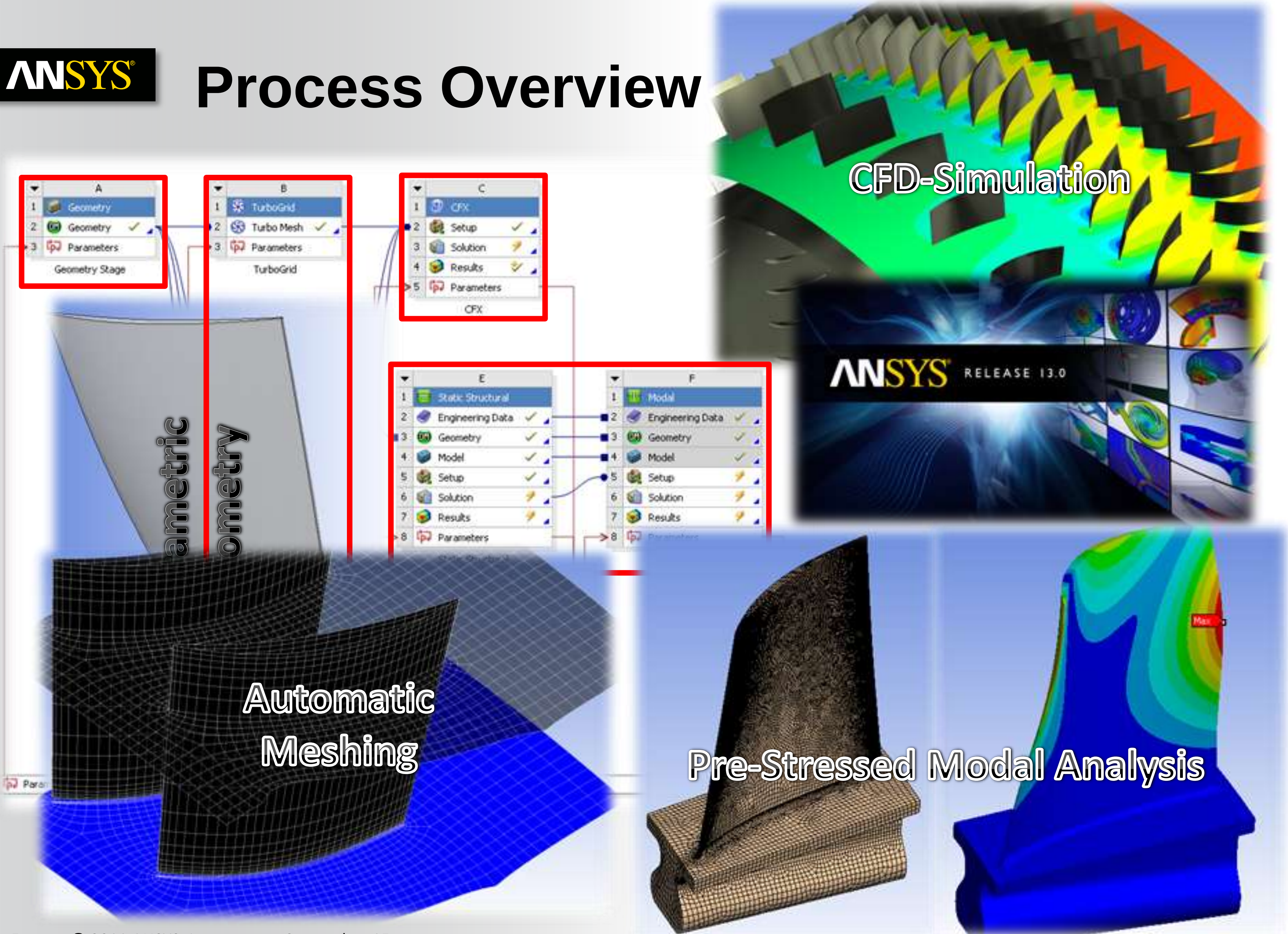
Process Overview



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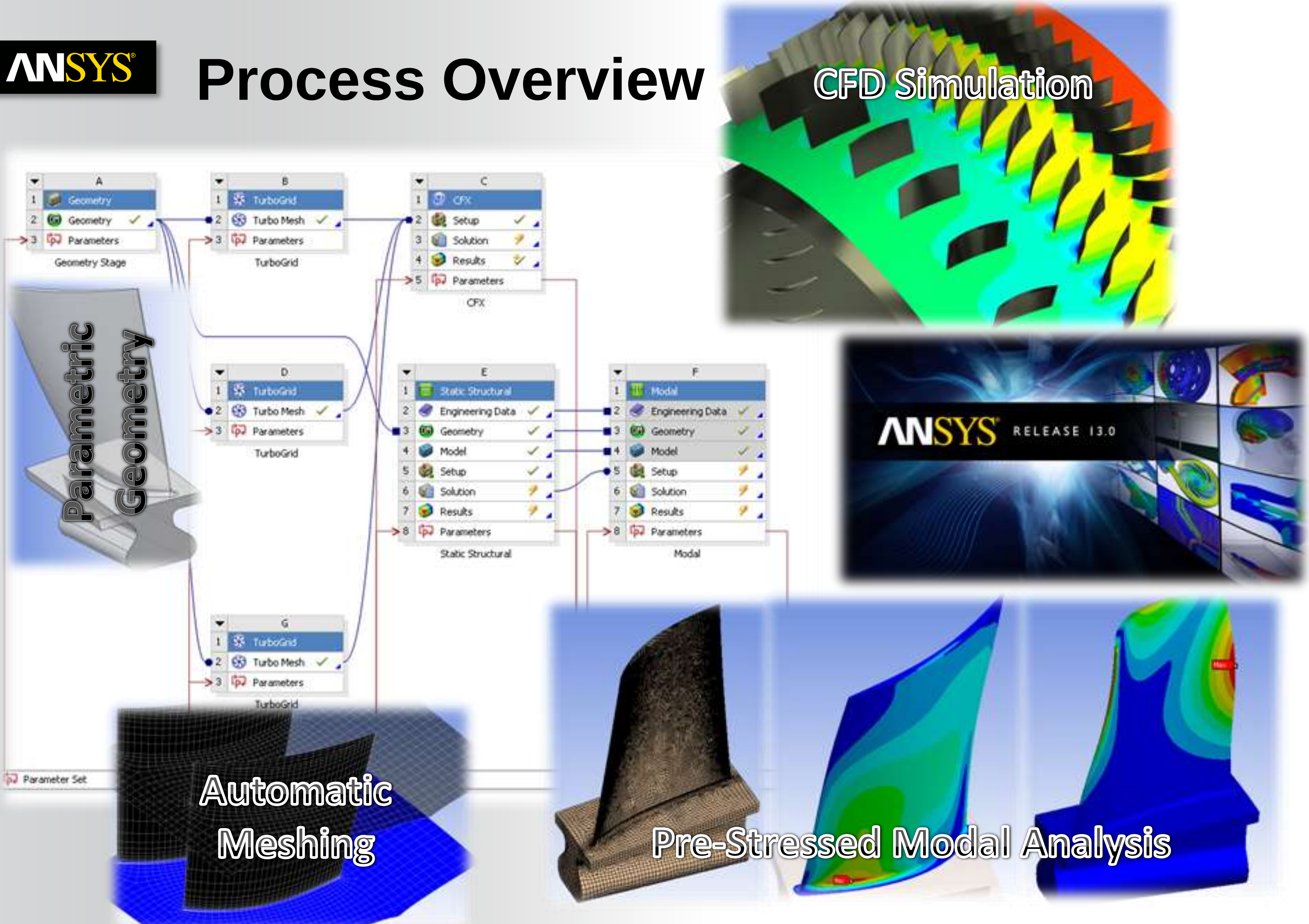
Process Overview



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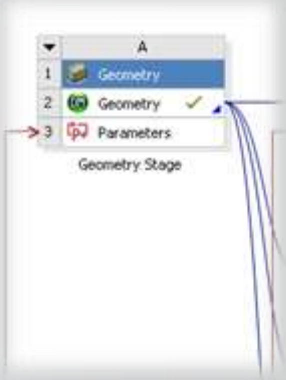
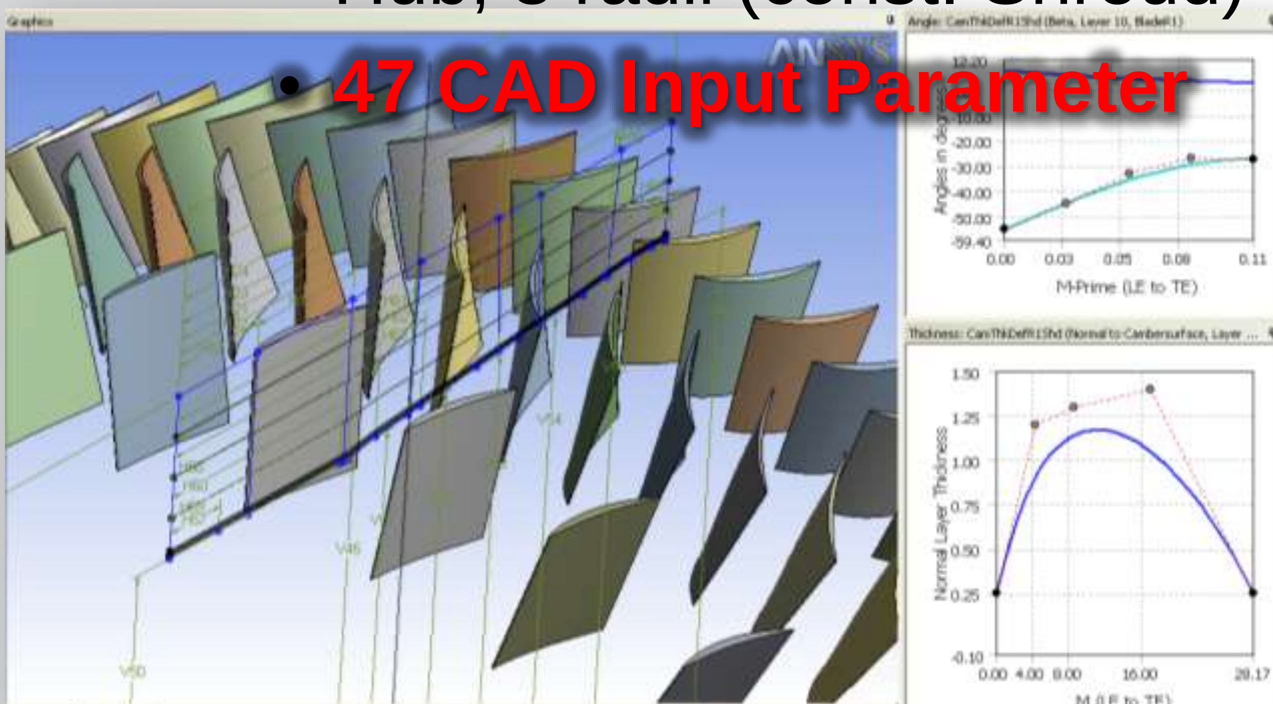
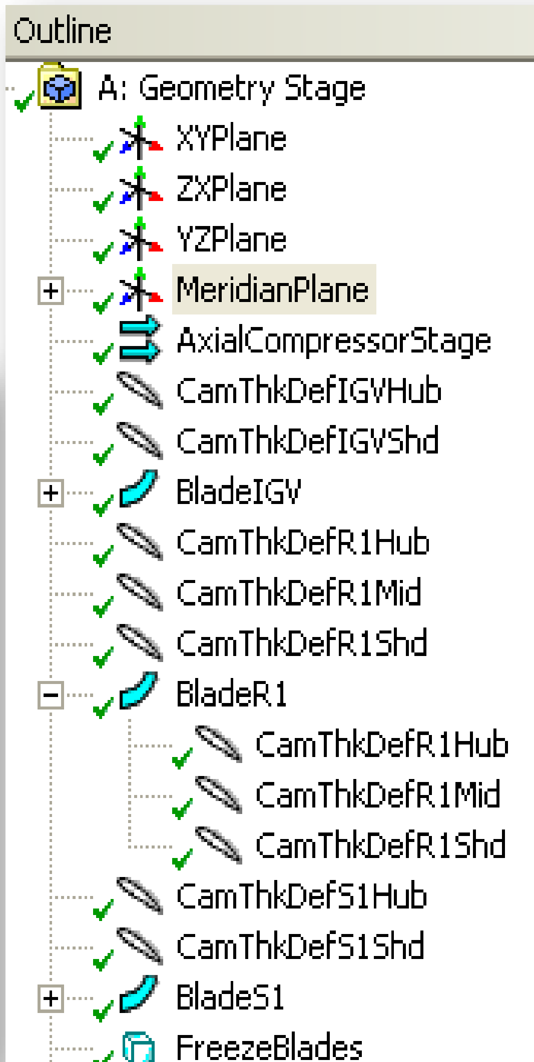
Geometry, Aero Dynamic



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





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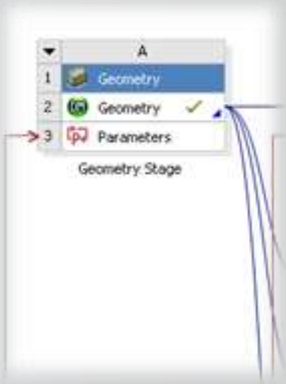
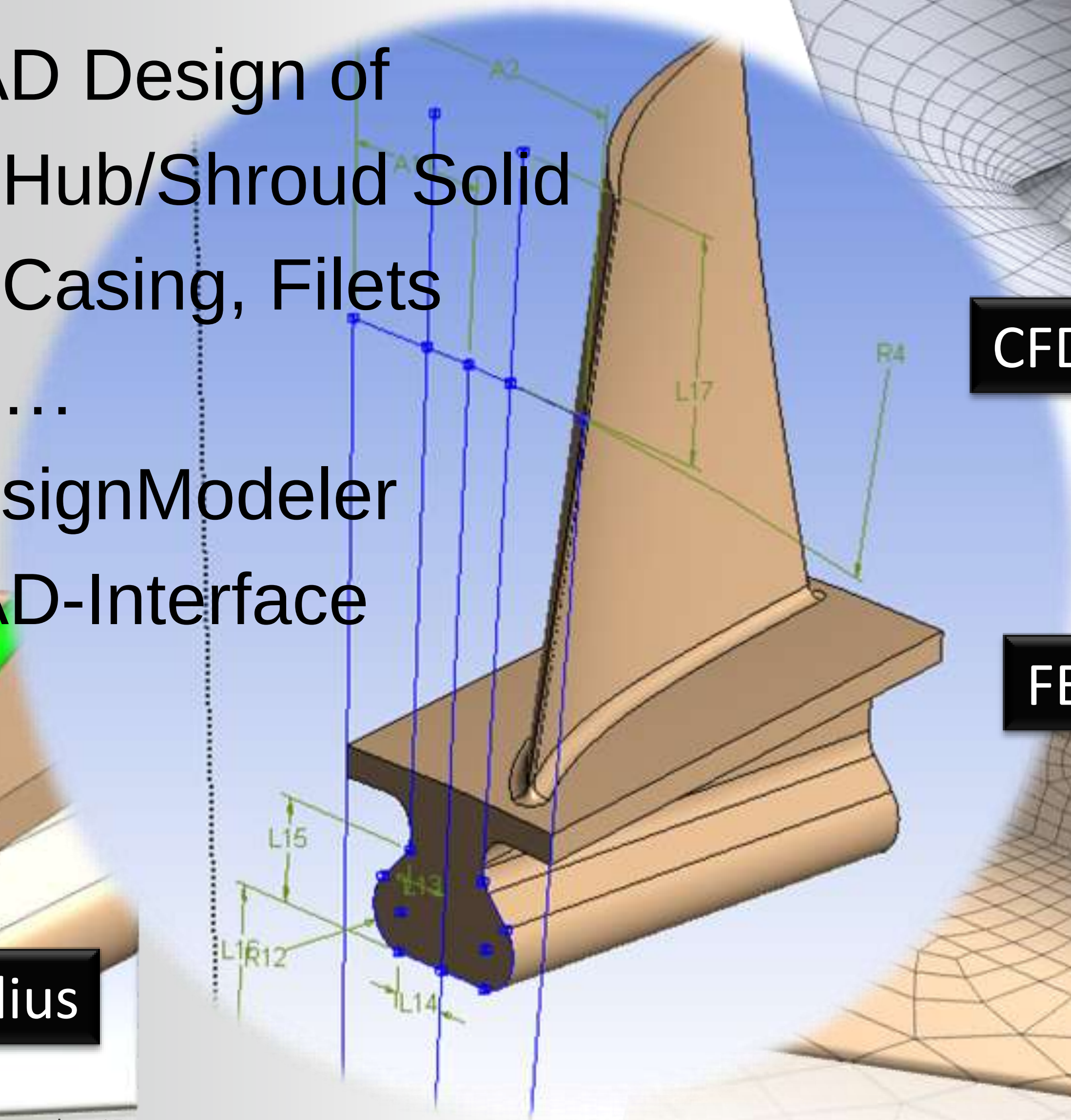
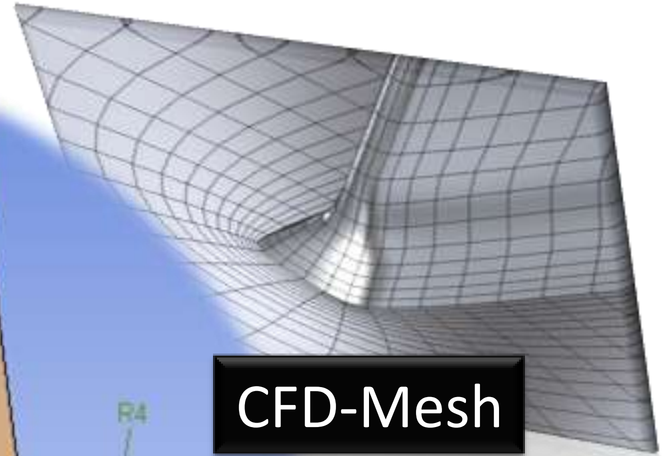
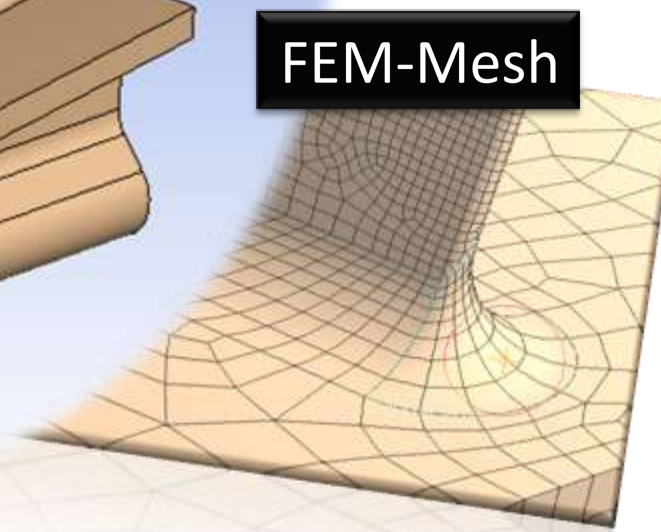
Geometry, Blade Design

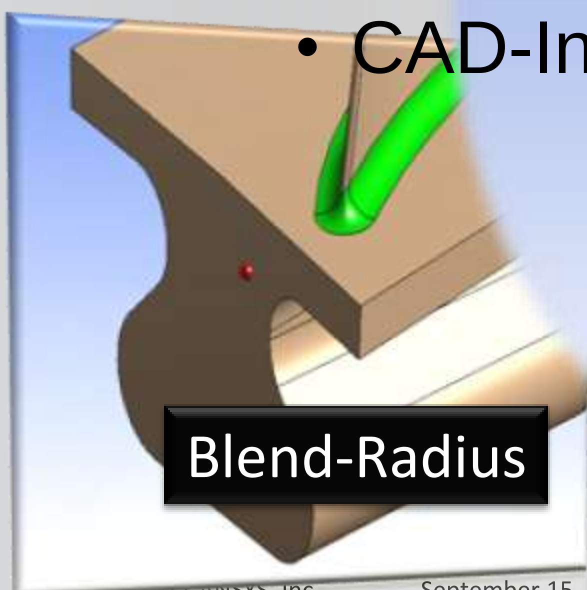


- CAD Design of
  - Hub/Shroud Solid
  - Casing, Filets
  - …
- DesignModeler
- CAD-Interface

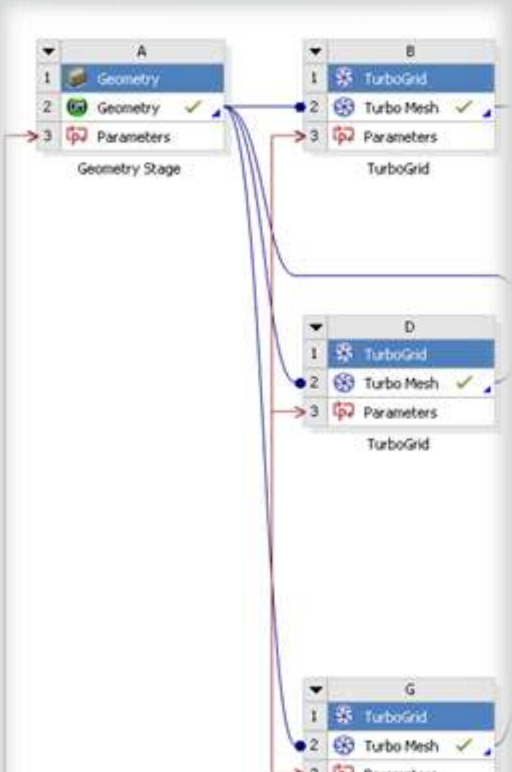




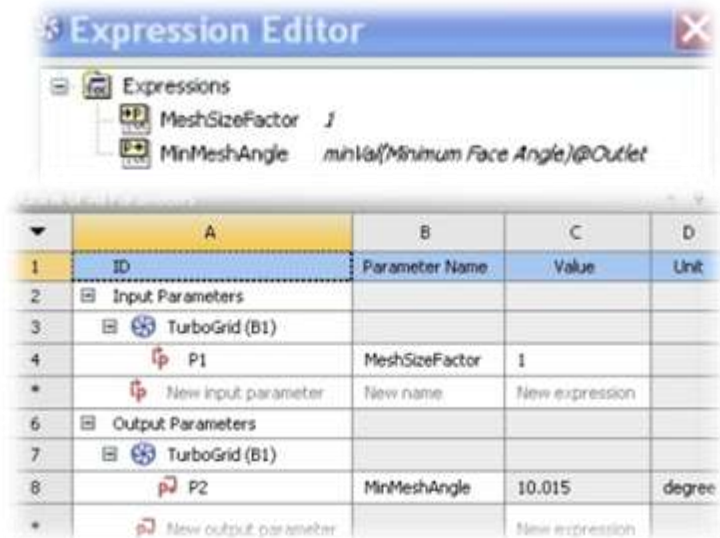


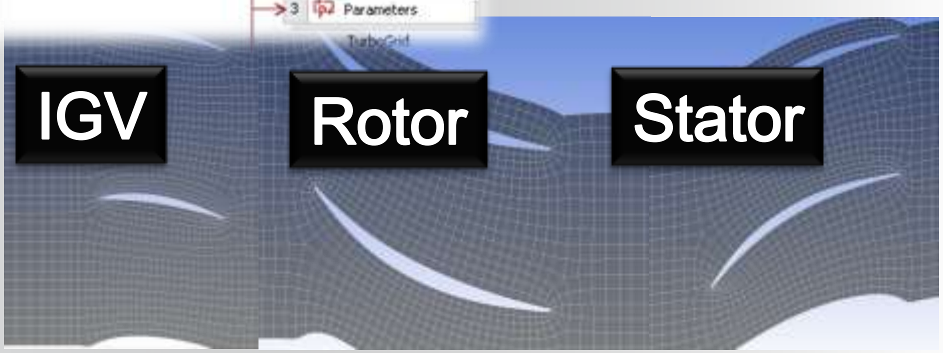


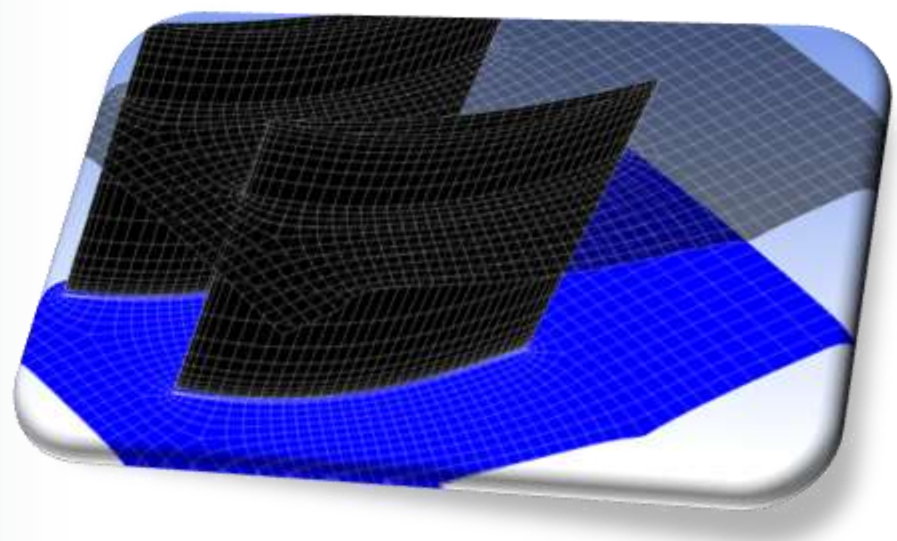
Meshing, TurboGrid



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







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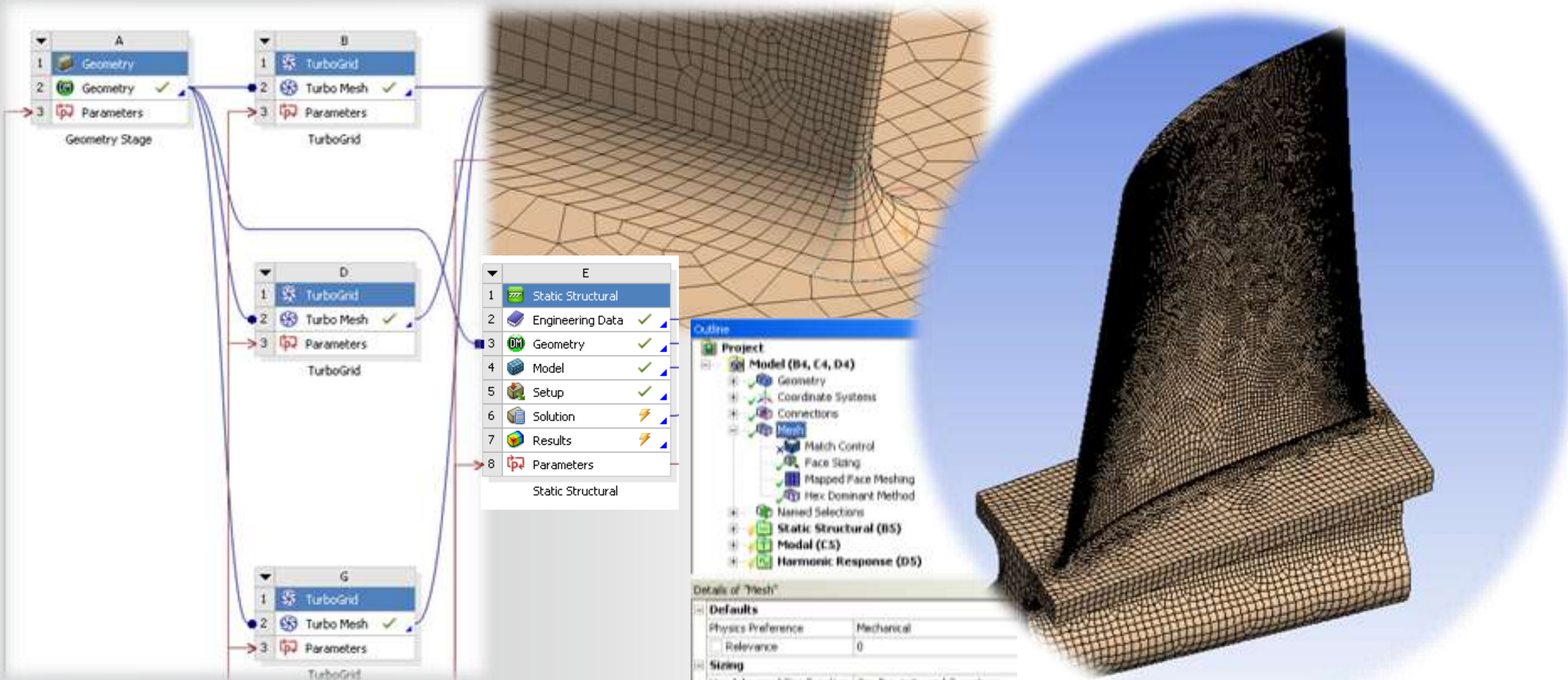
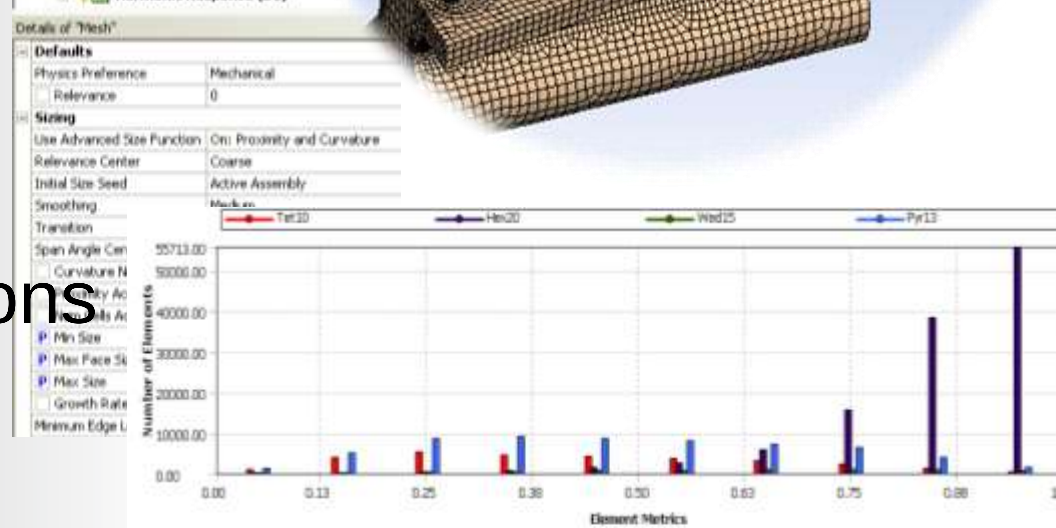
Meshing, General





- Hex-Dominant
- Automatic Size Functions
- …

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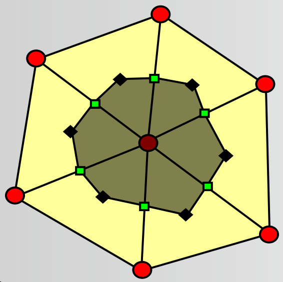
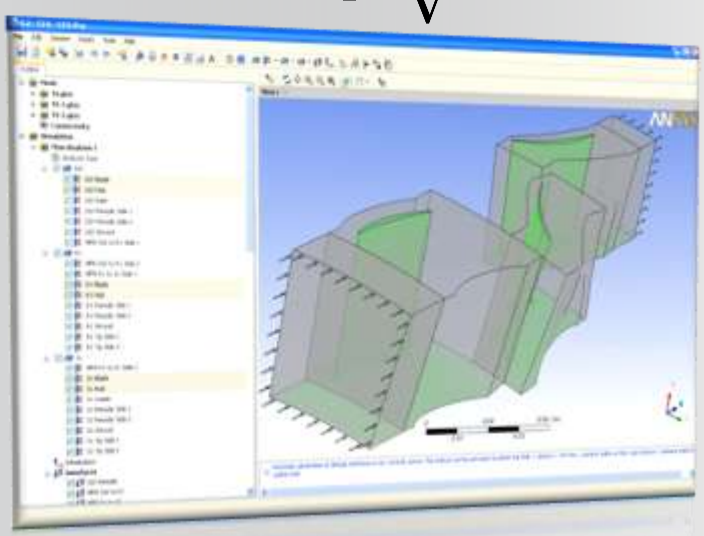
CFD Simulation



- **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
- **One sector by passage, MFR:**
  - Profile Transformation
  - Periodic Interface

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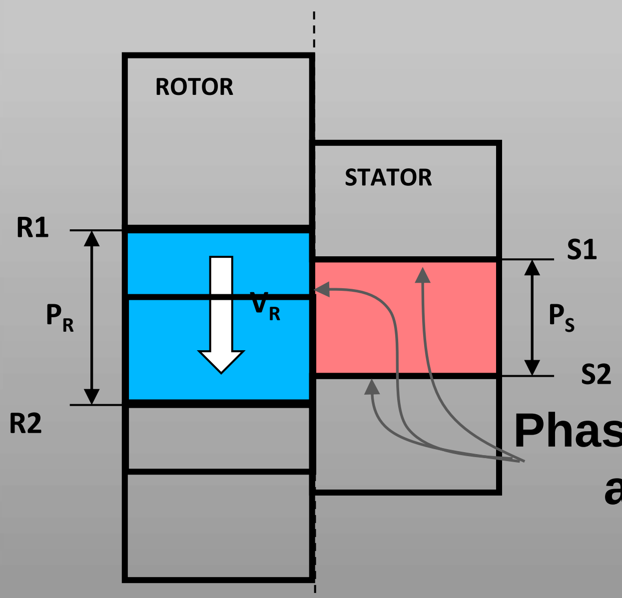
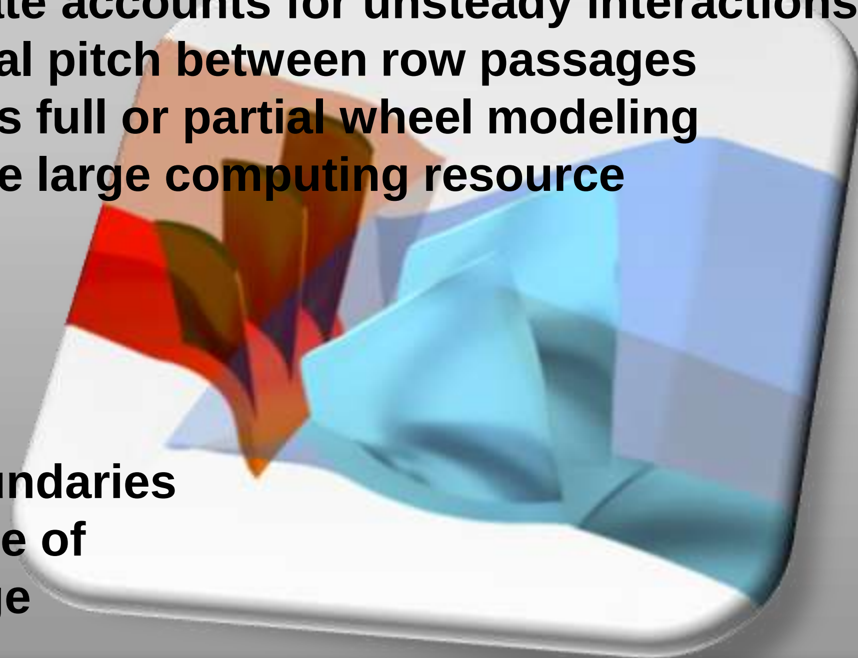
Transient Blade Row Method

Profile Transformation	Time Transformation	Fourier Transformation	Harmonic Transformation
Mixing Plane Frozen Rotor	Time Inclining	Shape Correction Phase Shift	f(t)→F(Ω) R&D

unequal pitch



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



Phase-shifted boundaries a consequence of pitch change

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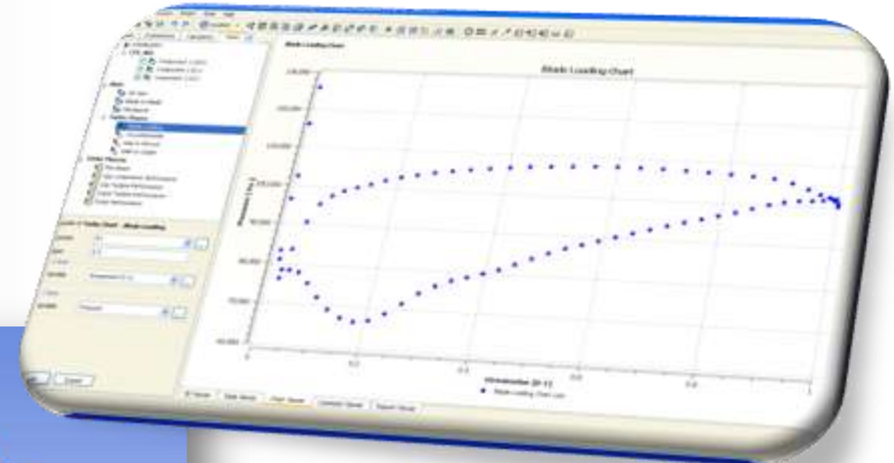
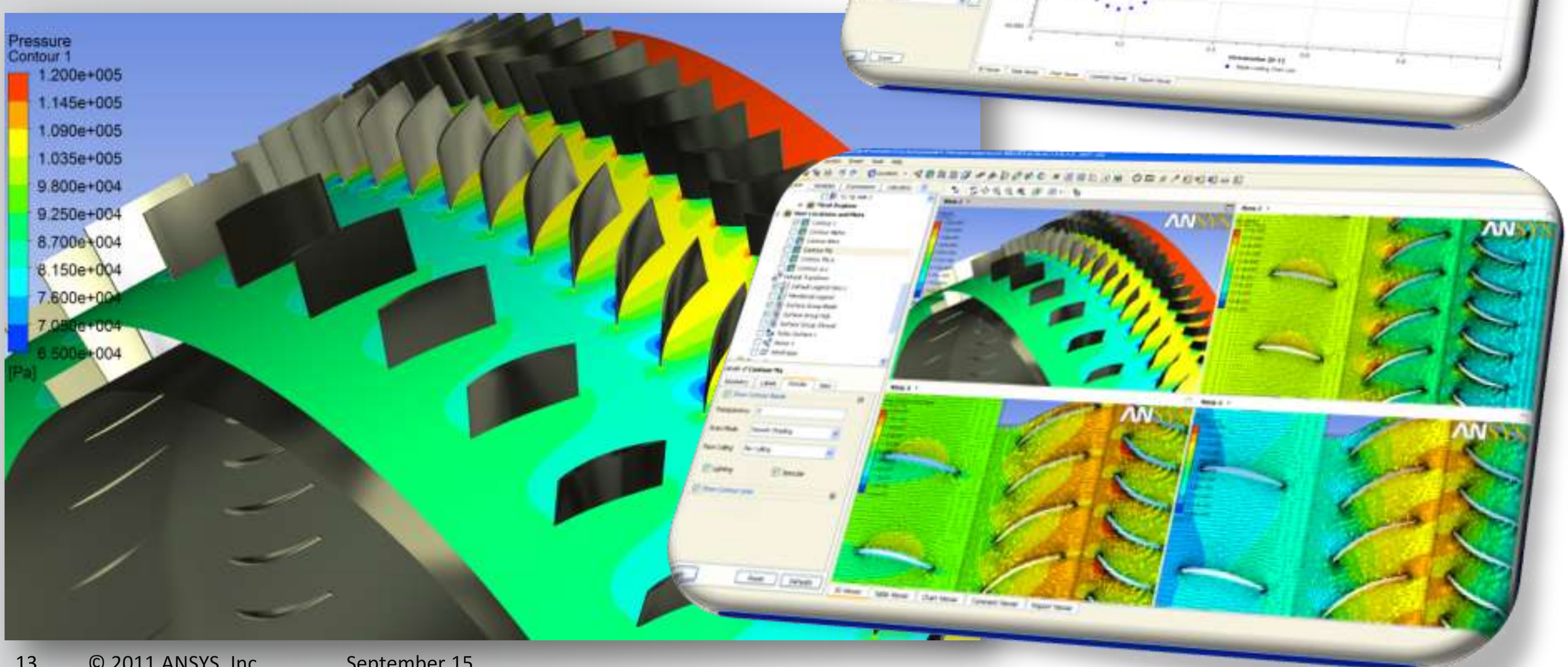
CFD Post-Processing

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





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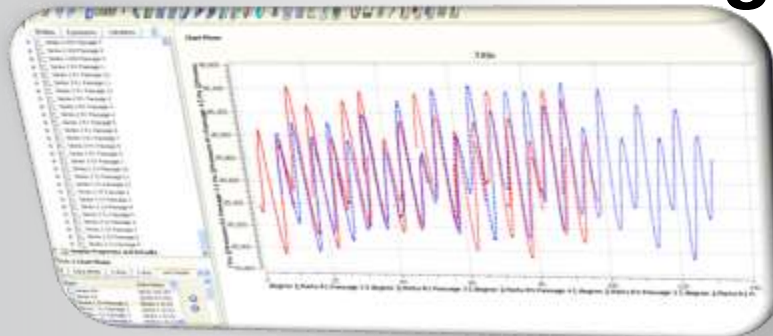
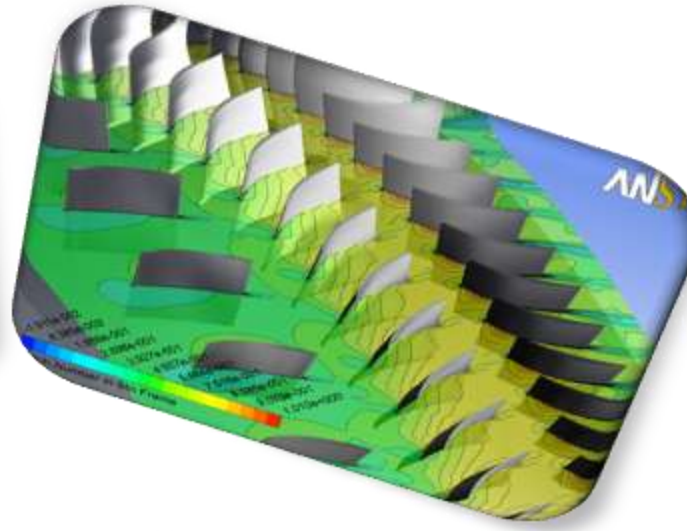
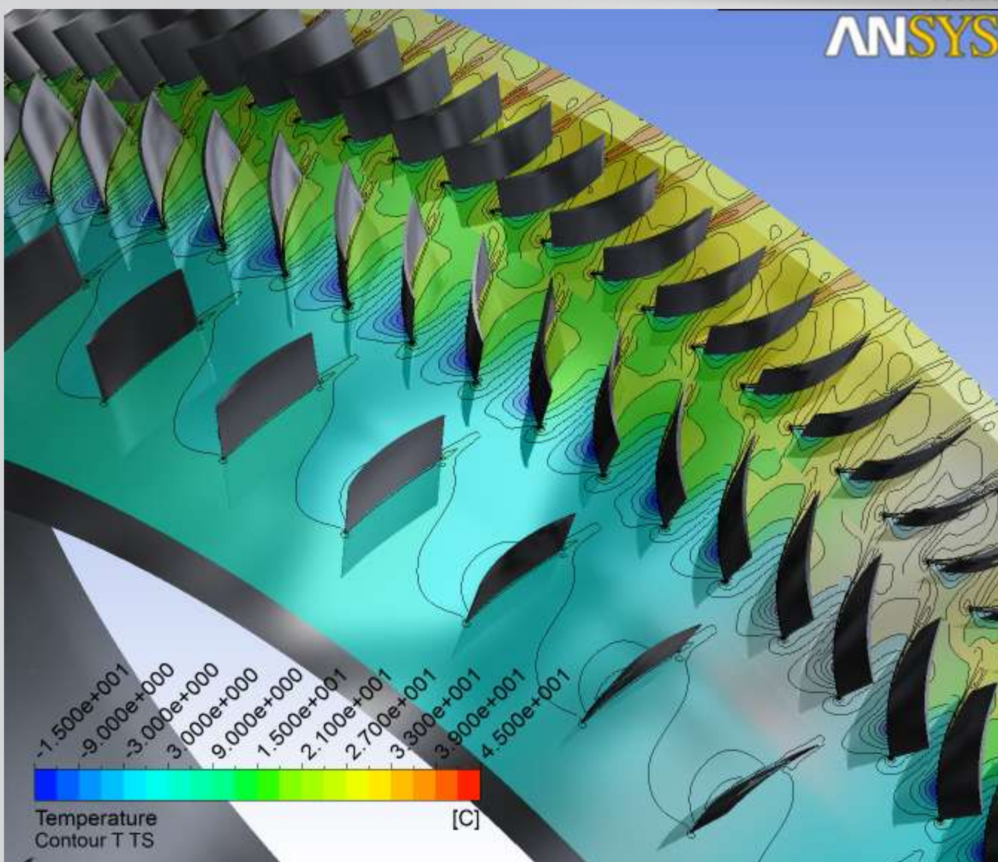
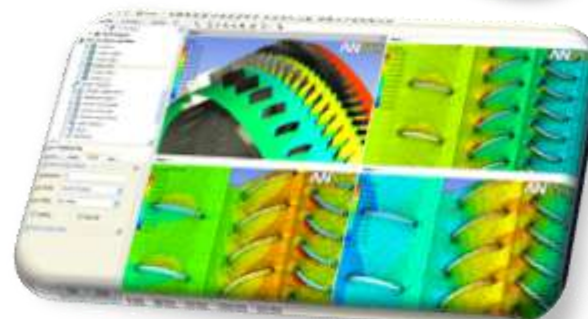
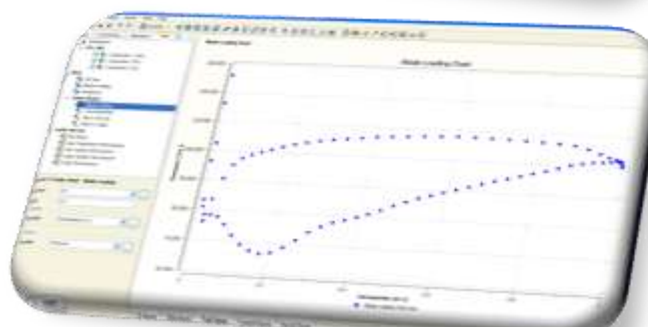
CFD Post-Processing



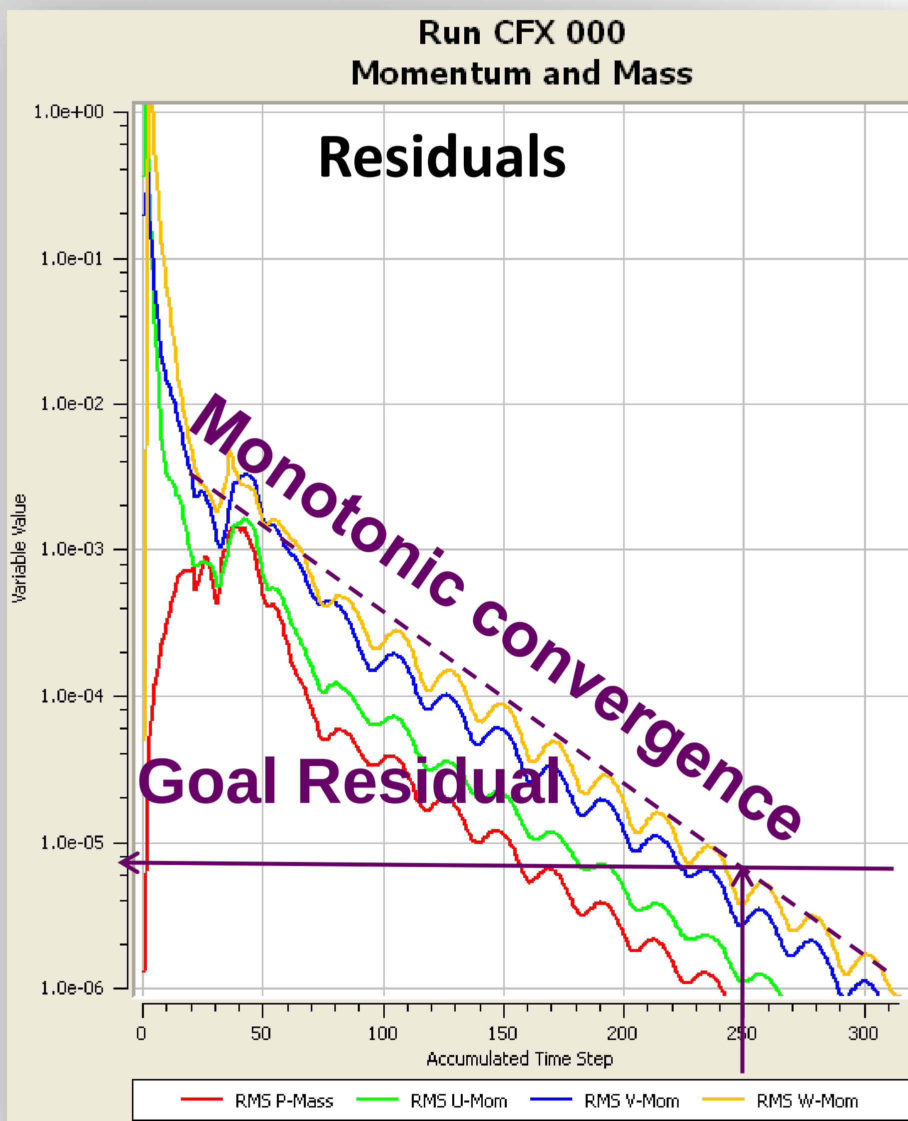


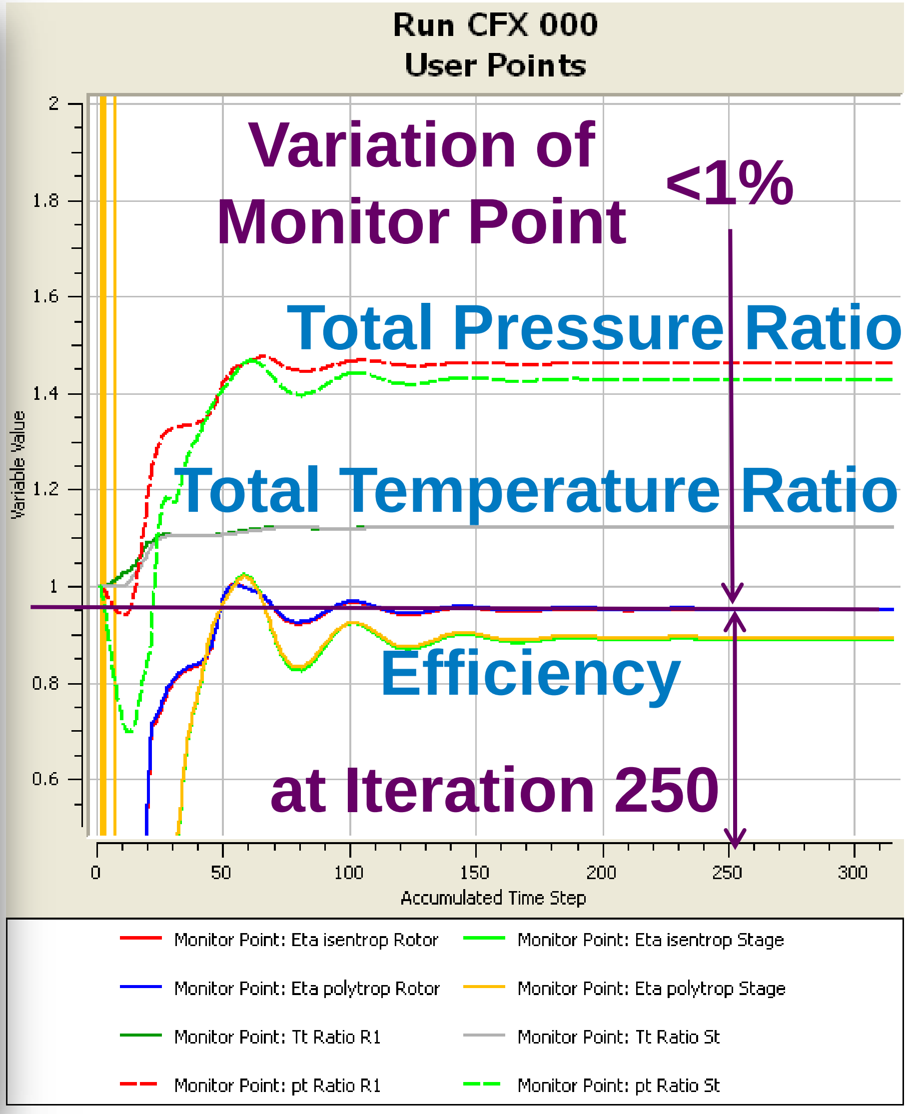






Quality Assurance Iteration Error





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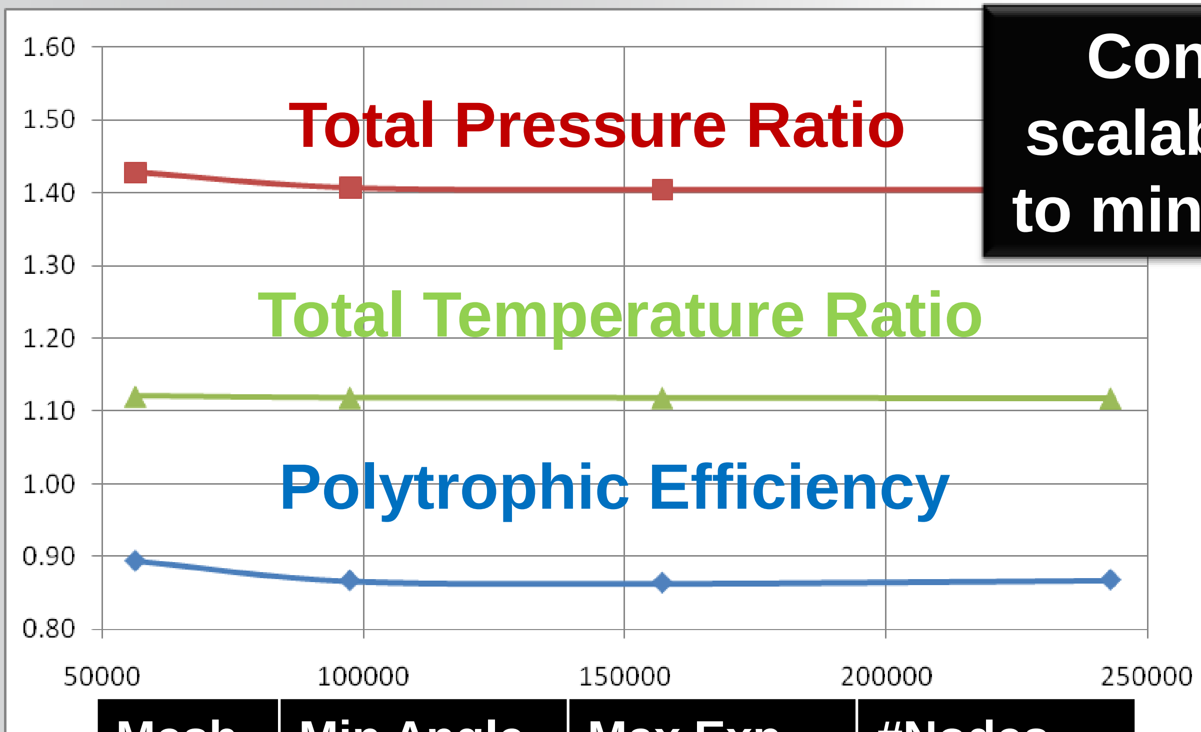
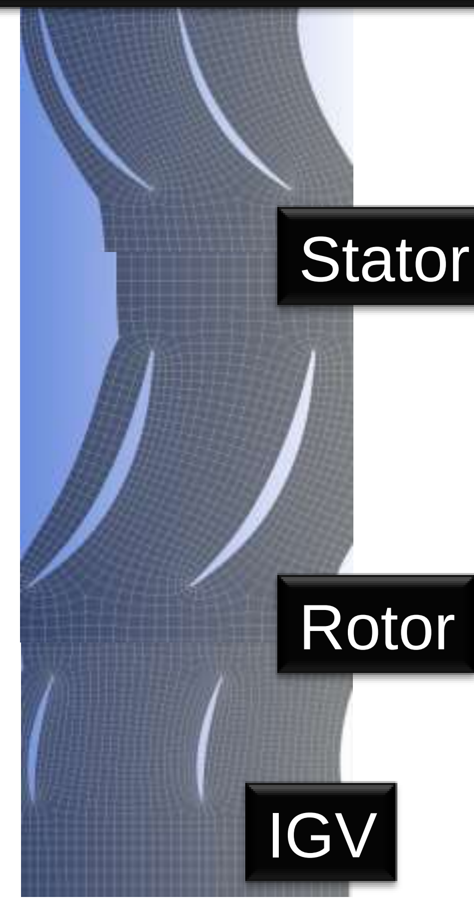
Quality Assurance Discretization Error



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

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Mechanical Simulation Procedure

- **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)**

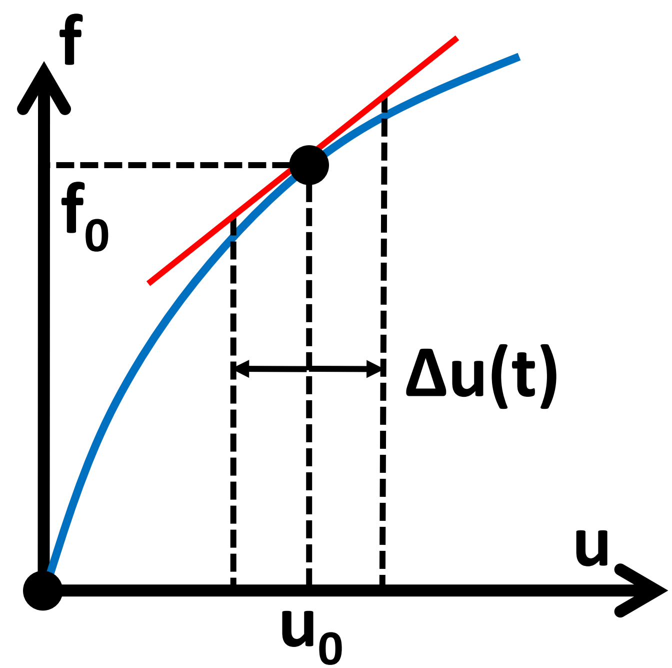
$$K(u_0) \cdot u_0 = f_0$$

- **Modal Analysis**

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

- **Linear dynamic System**

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



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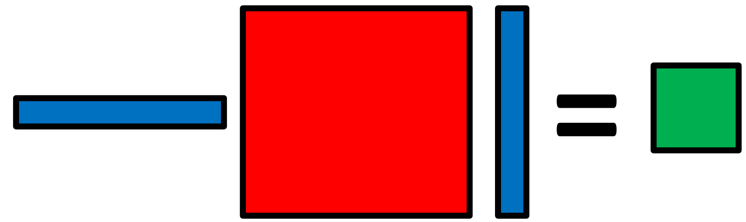
Model Order Reduction

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



- 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

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

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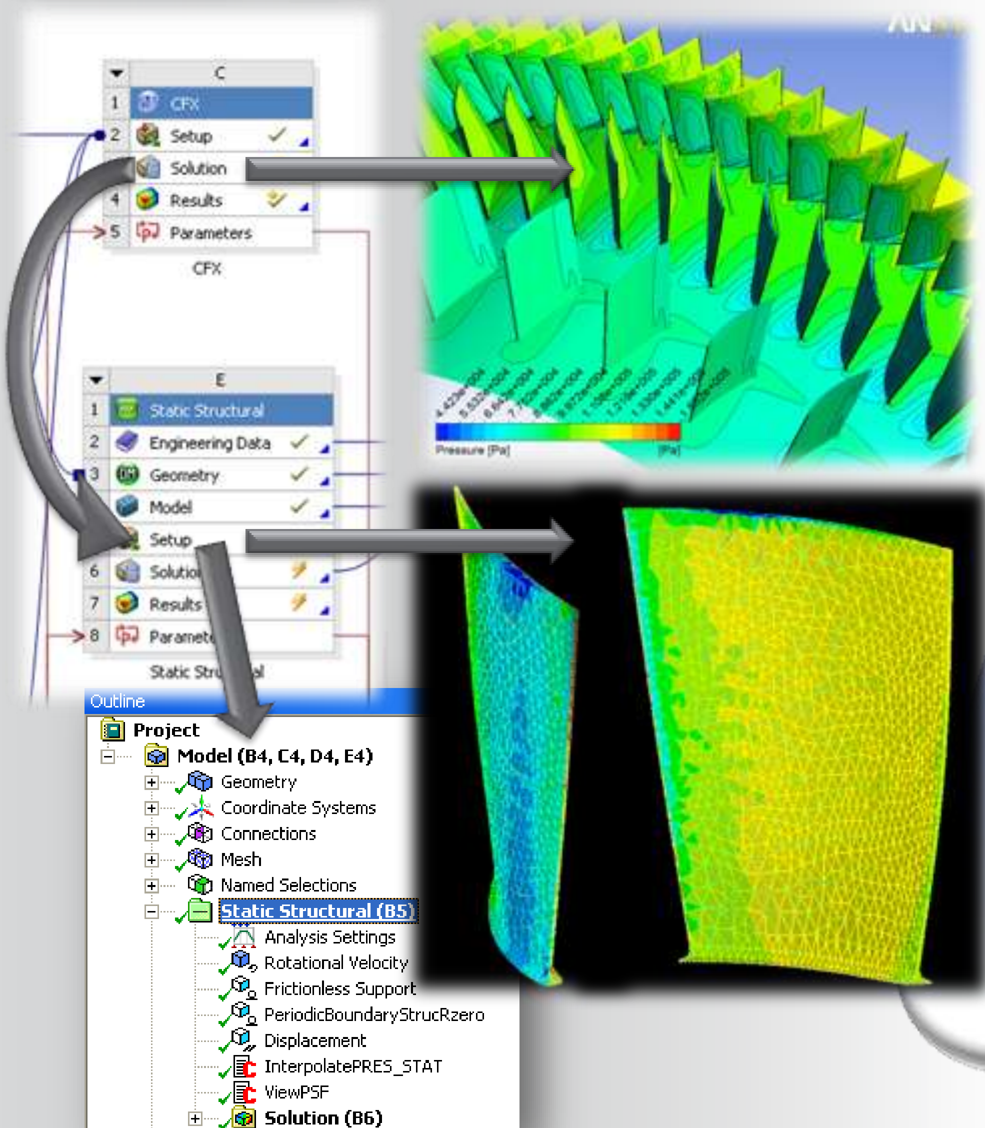
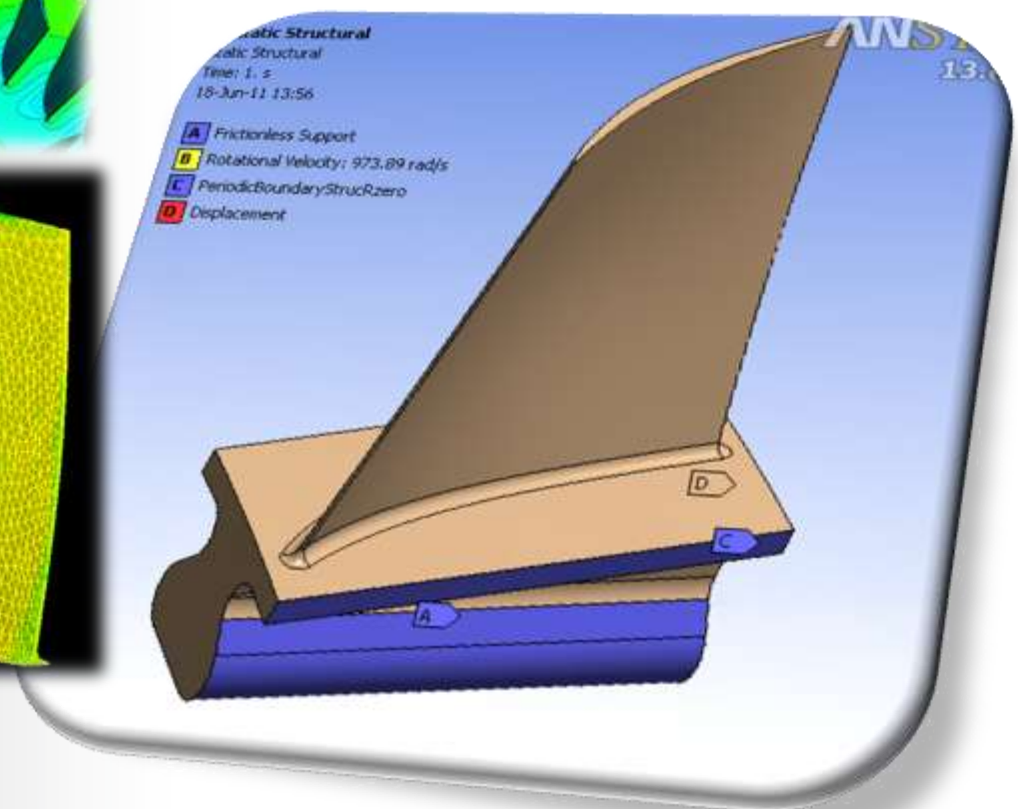
Fluid-Structure Coupling



- Displacements
- Rot. Velocity
- CFD-Pressure



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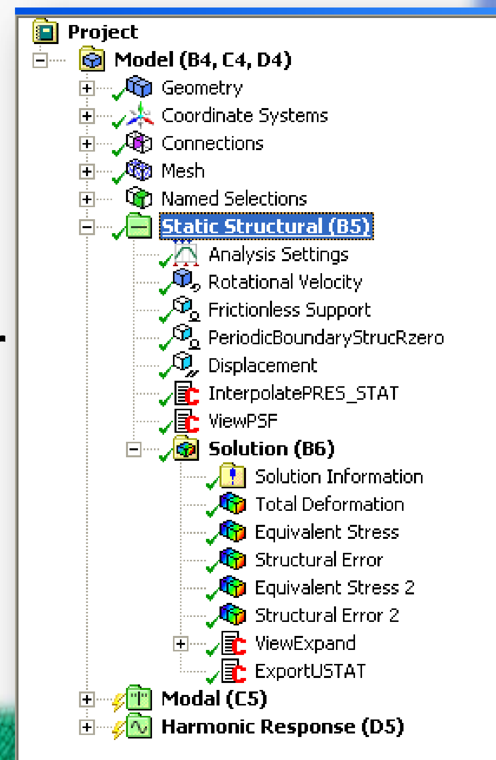
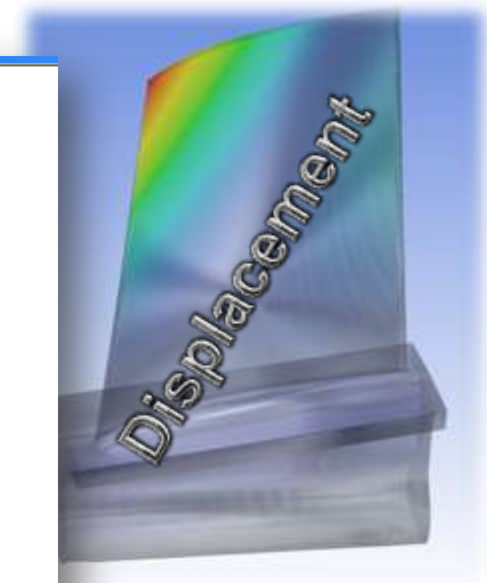
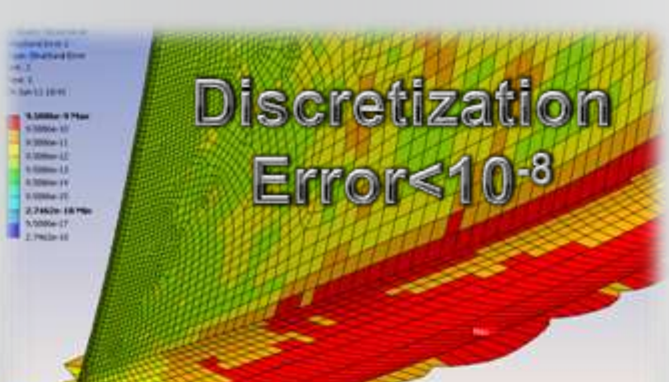
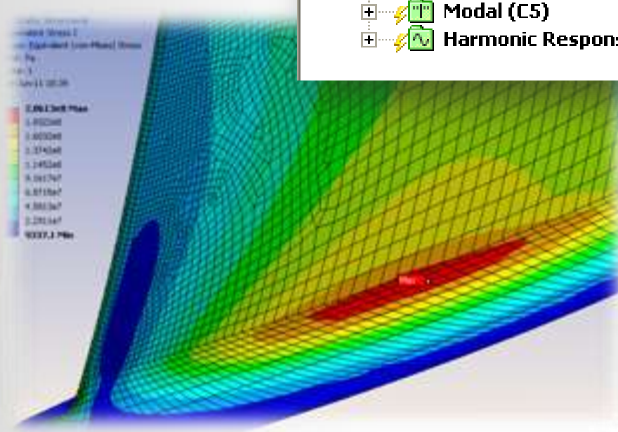
Static Structural (Pre-Stress)

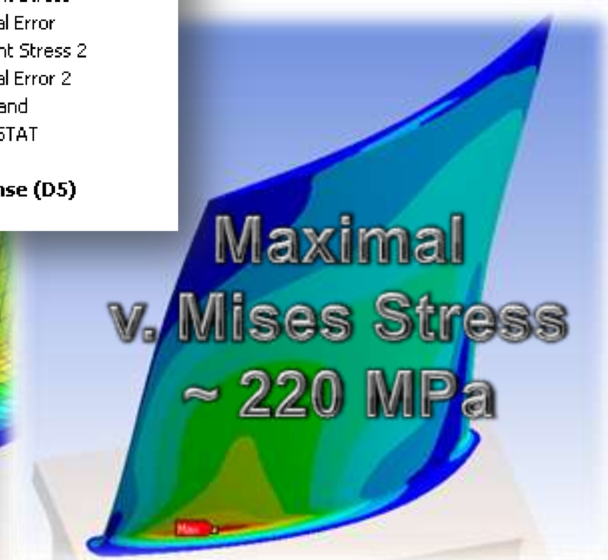
- Static Solution:
  - Displacement
  - Strain & Stress
  - Numerical Error
  - Pre-Stress for further Analysis











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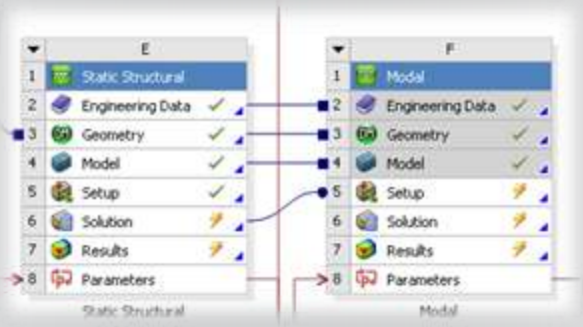
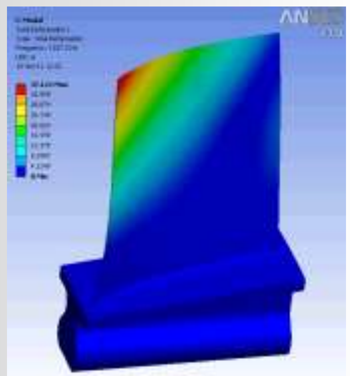
Modal Analysis



	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

1



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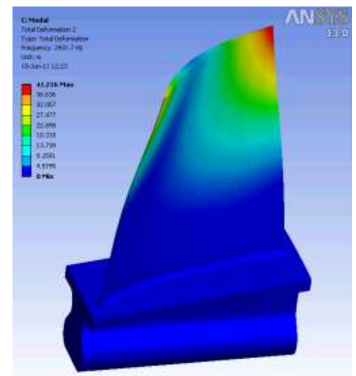

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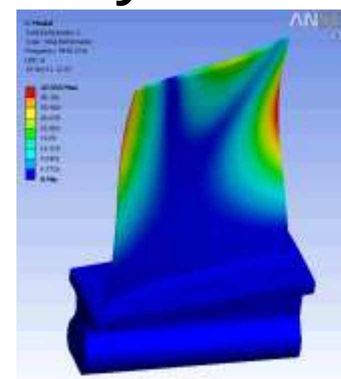

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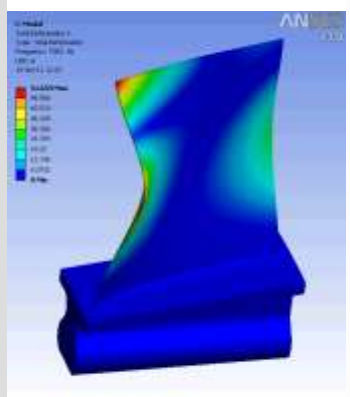

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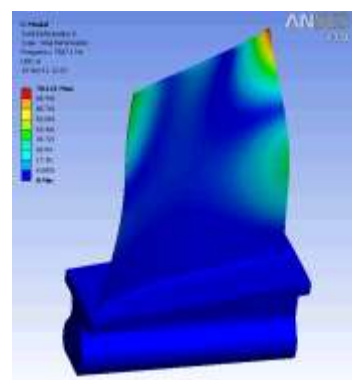

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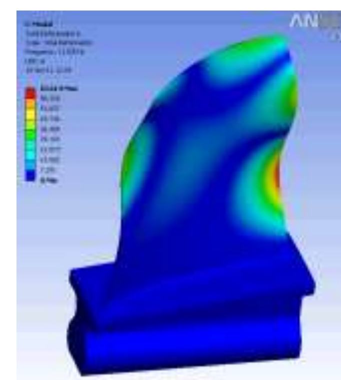

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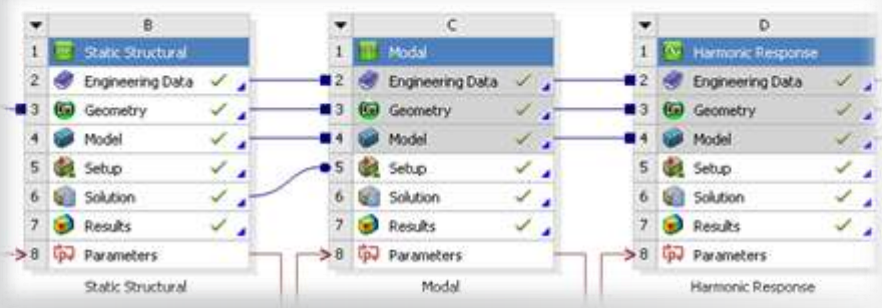
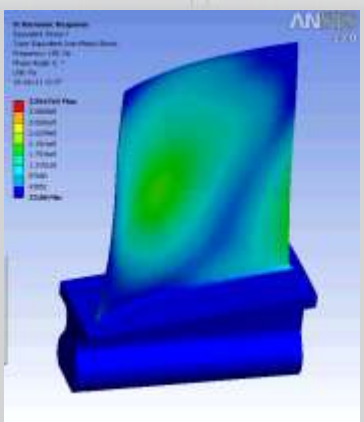
Forced Response Analysis



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

1



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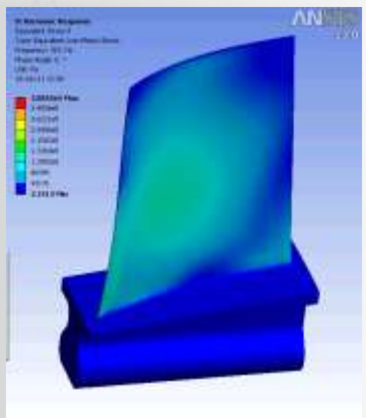

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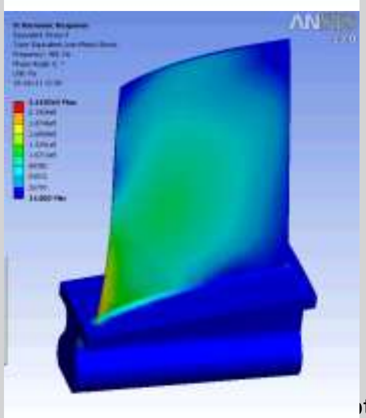

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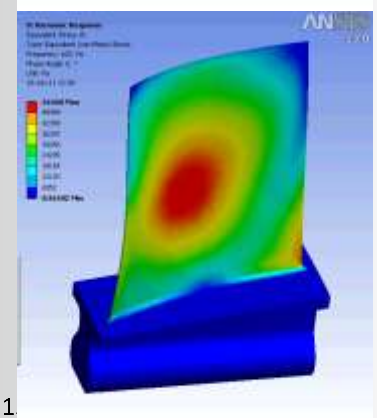

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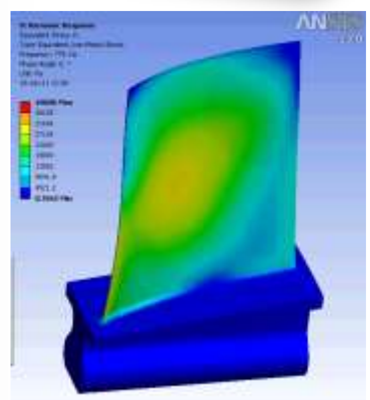

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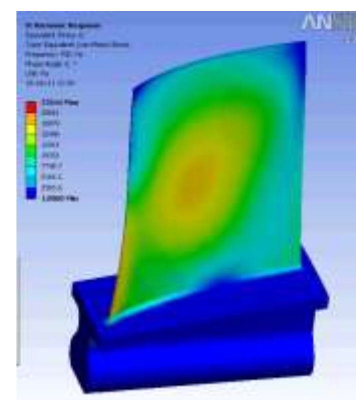
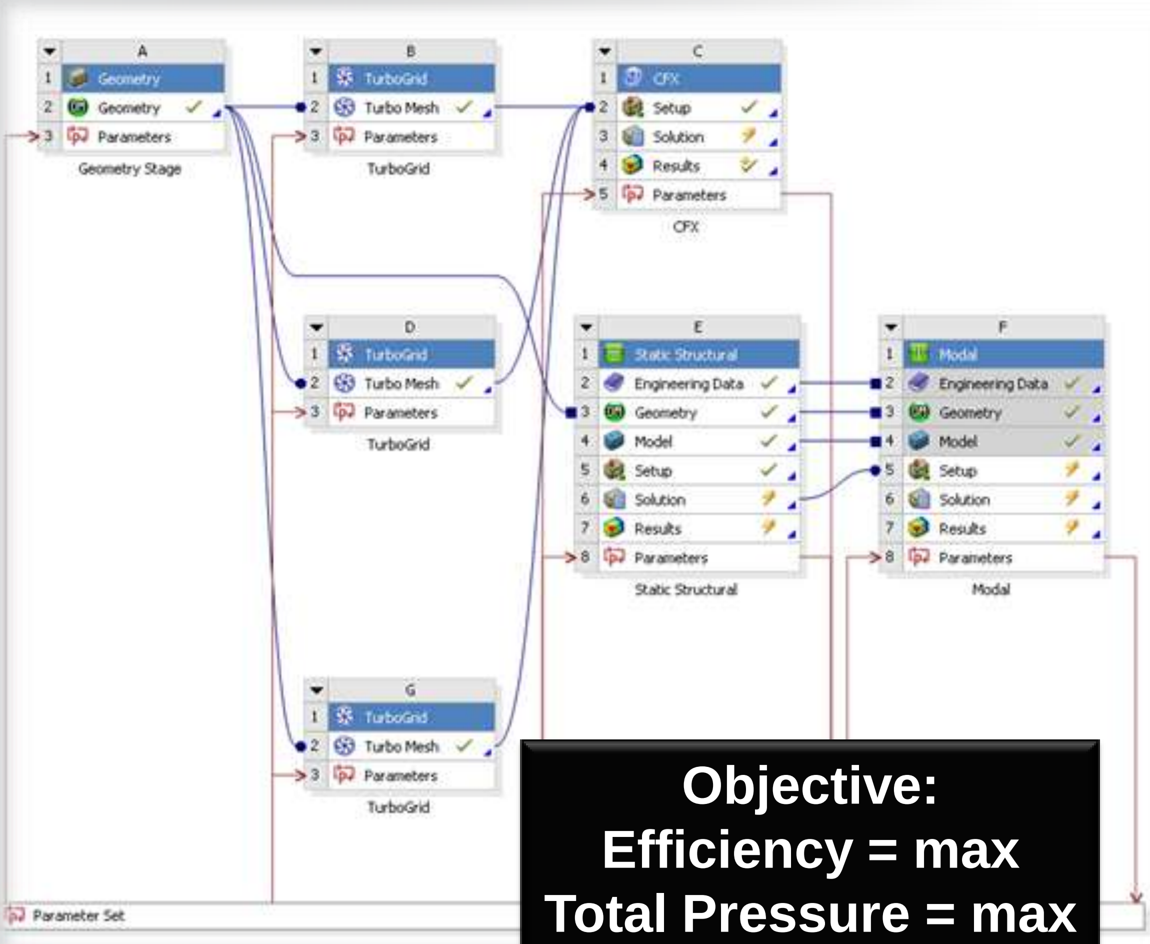


Process Summary and Objectives



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

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optiSLang Integration/Interface

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

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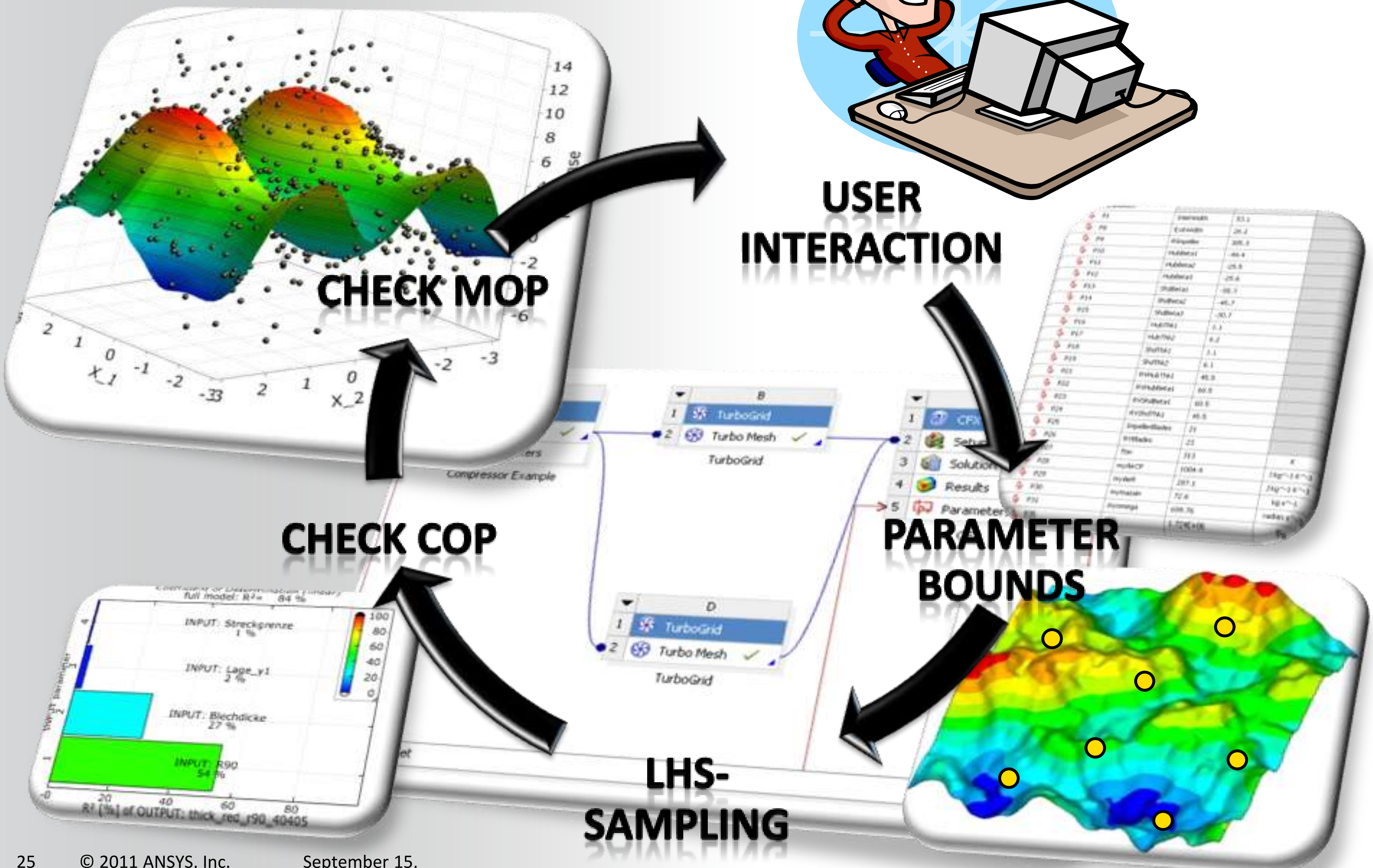
Sensitivity Analysis



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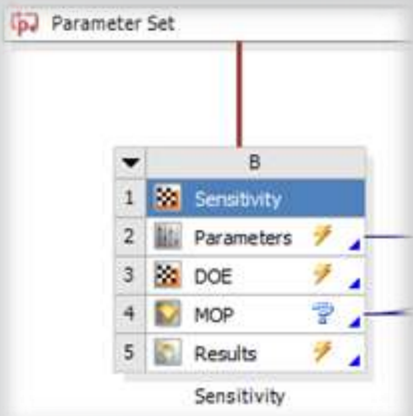
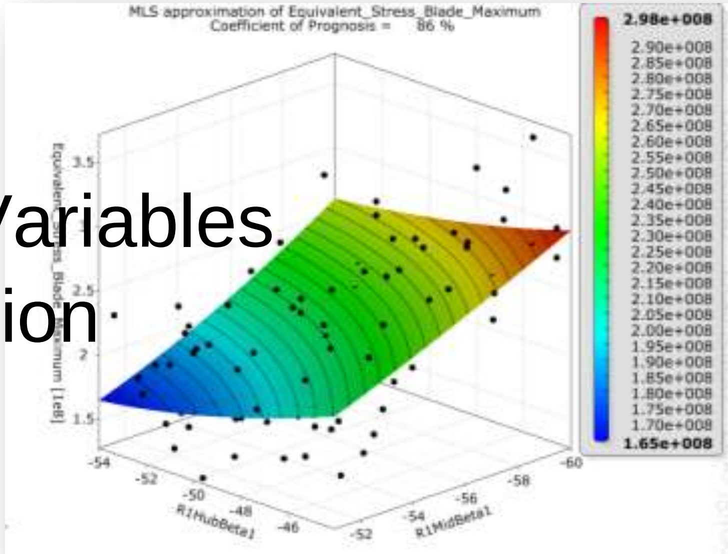
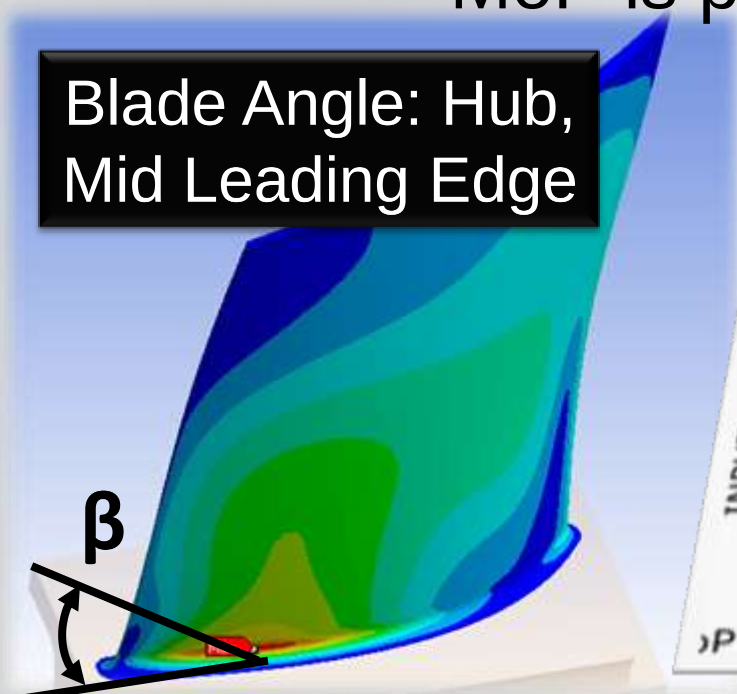
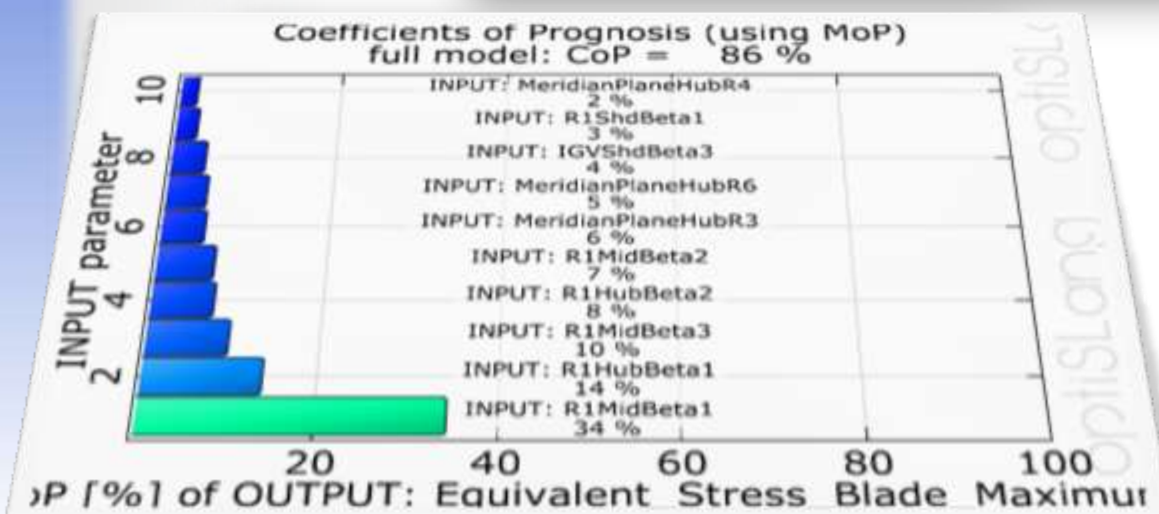
Sensitivity Analysis, Maximal Stress



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







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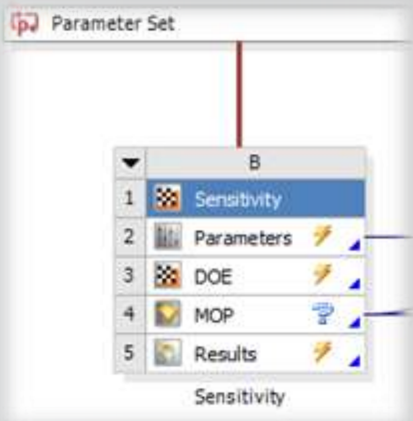
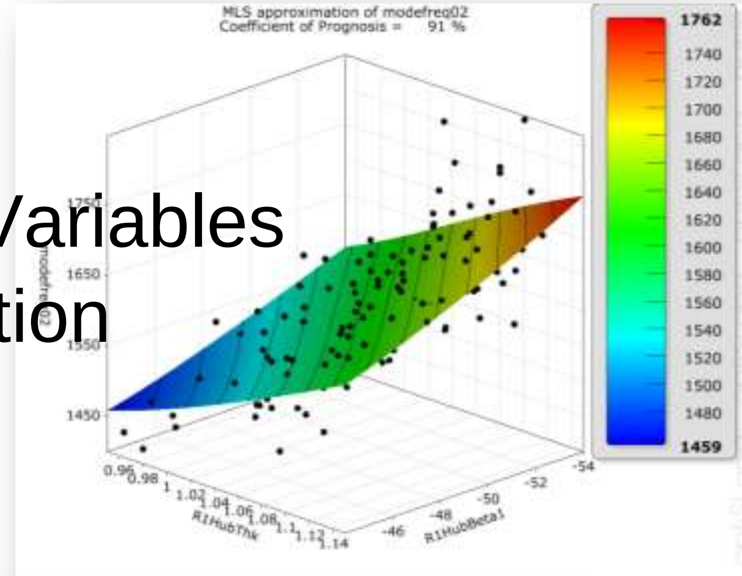
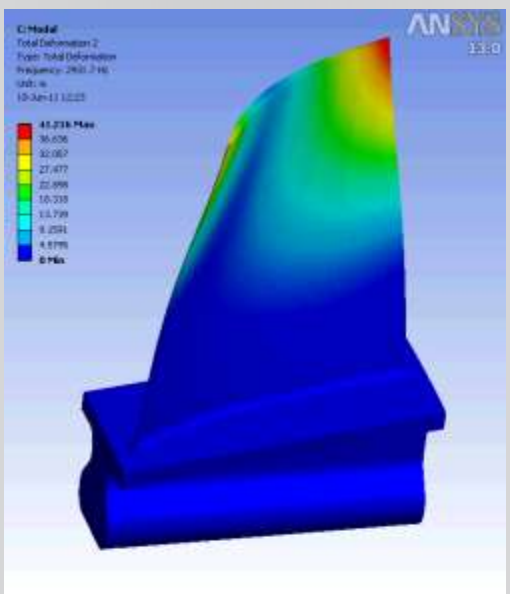
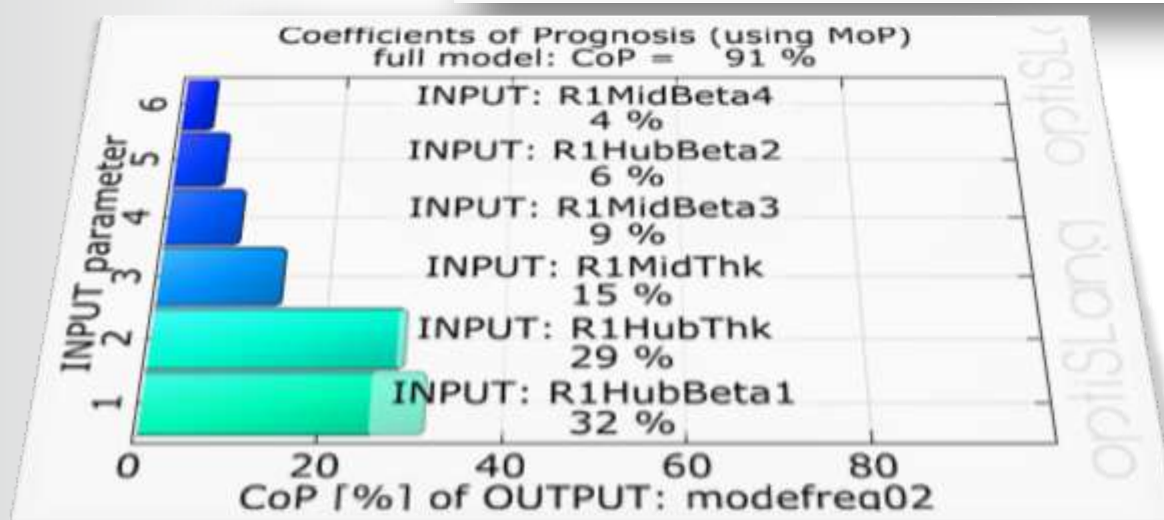
Sensitivity Analysis, Eigen Mode 2



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







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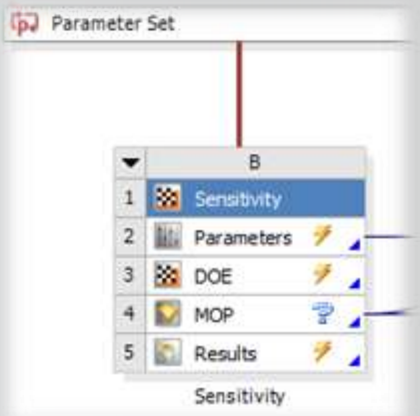
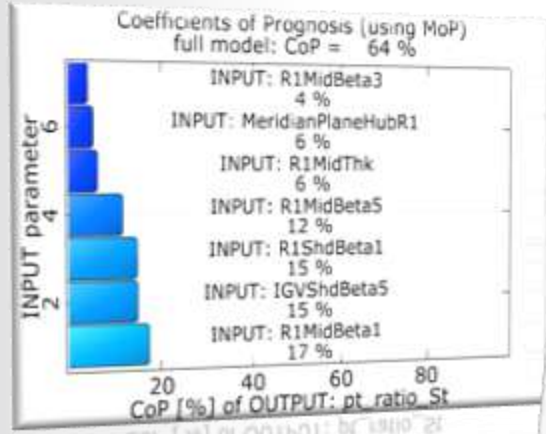
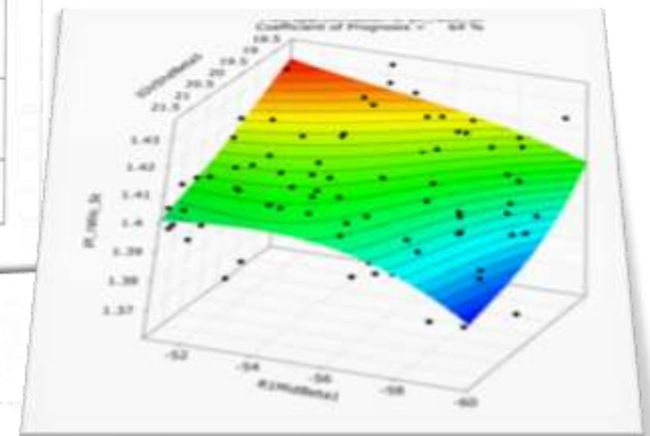
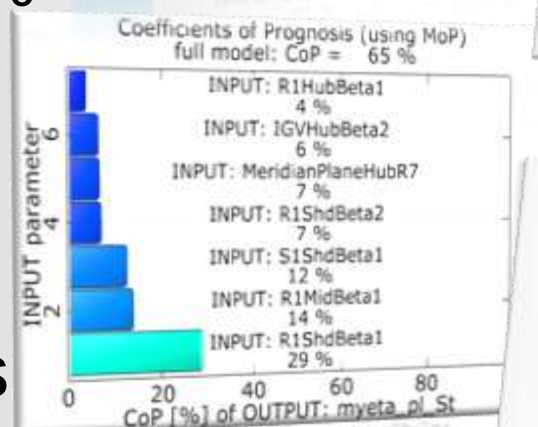
Sensitivity Analysis, Aero Dynamic

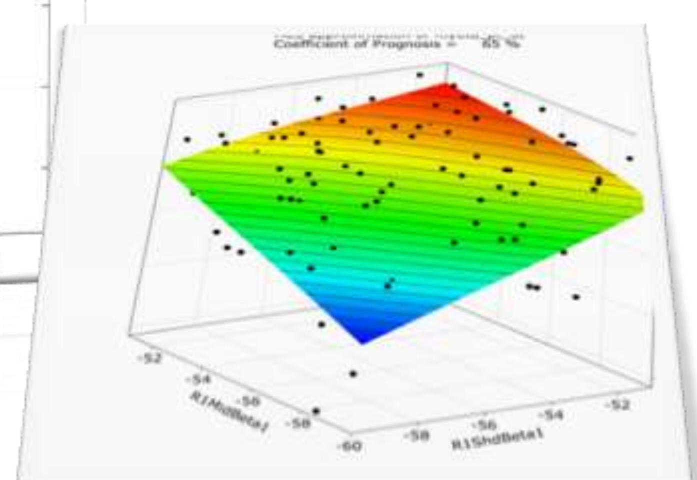






- CoP=64% and 65%
  - small value
  - Numerical error?
  - Model error?
- Important Variables
  - Parameter Reduction
- MoP is plausible





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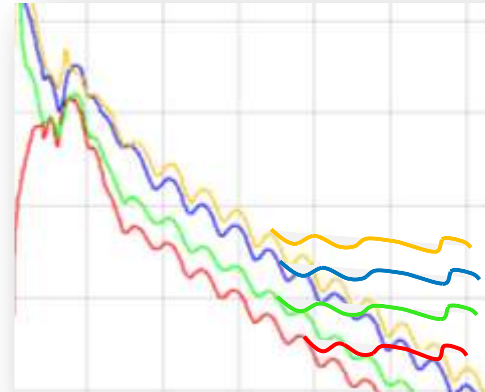
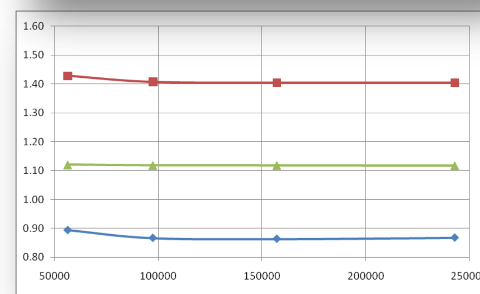
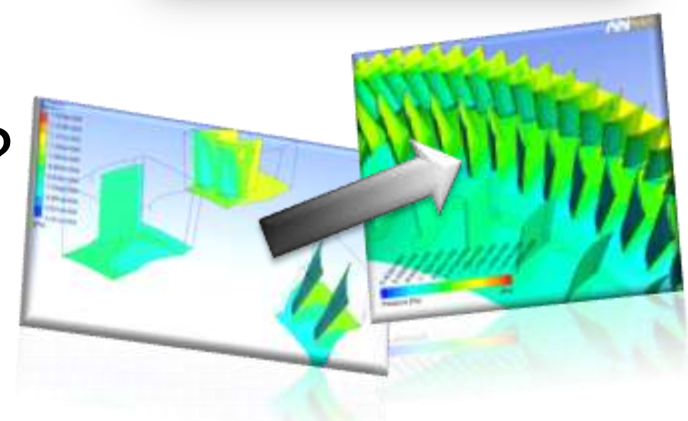
Trouble Shooting with small CoP

- 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“!







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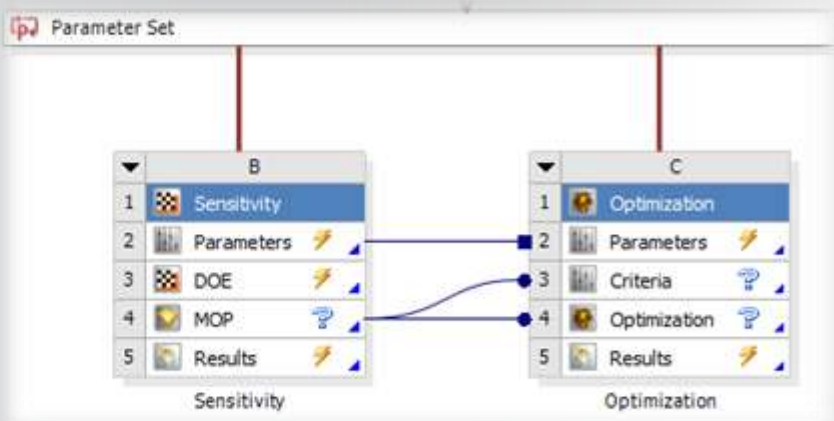
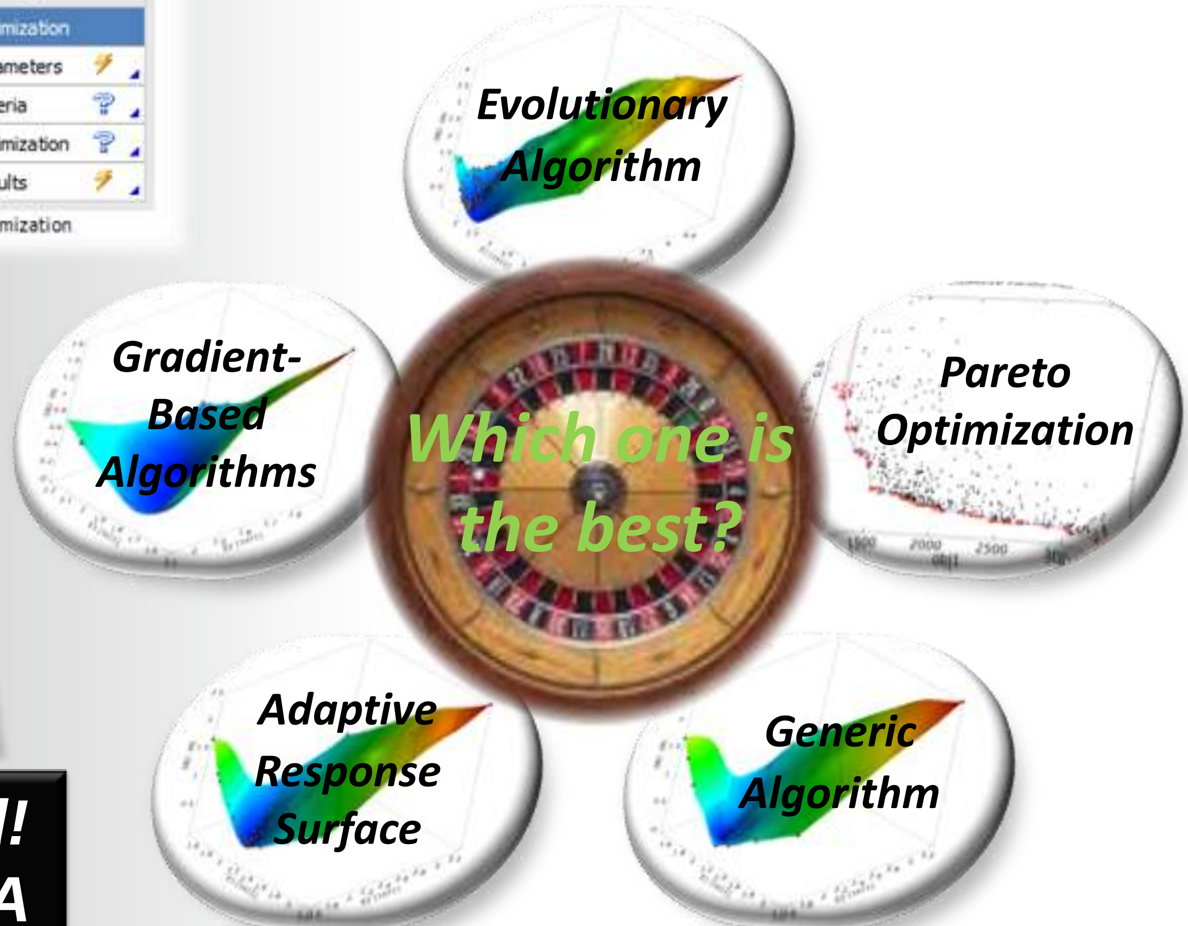
Design Optimization

Optimization Algorithms:





Strategy is required! and derived from SA

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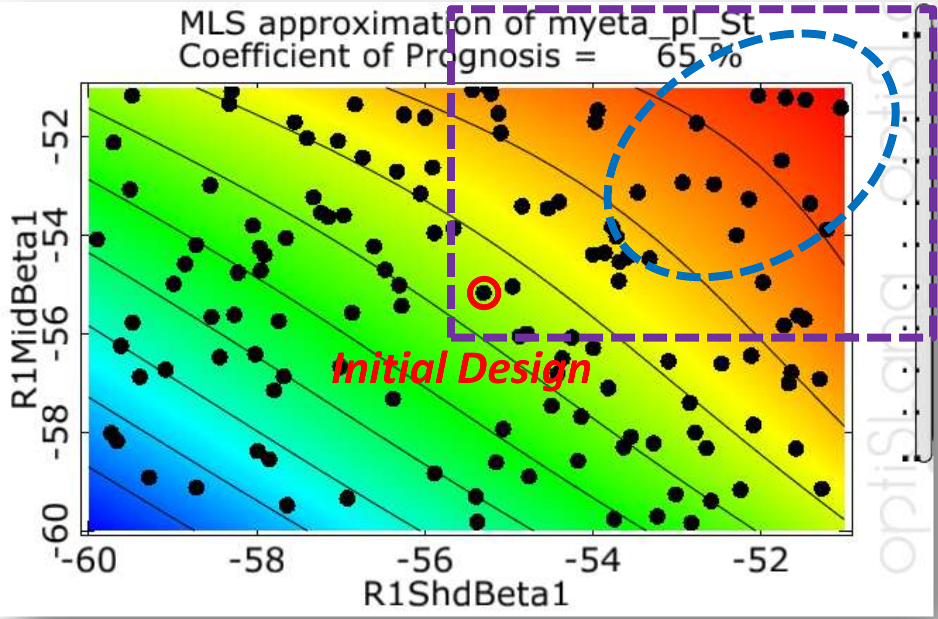
Design Optimization, Strategy

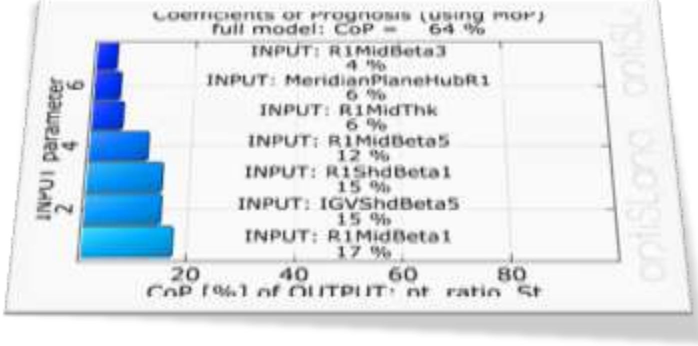
Sensitivity Analysis:

- 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



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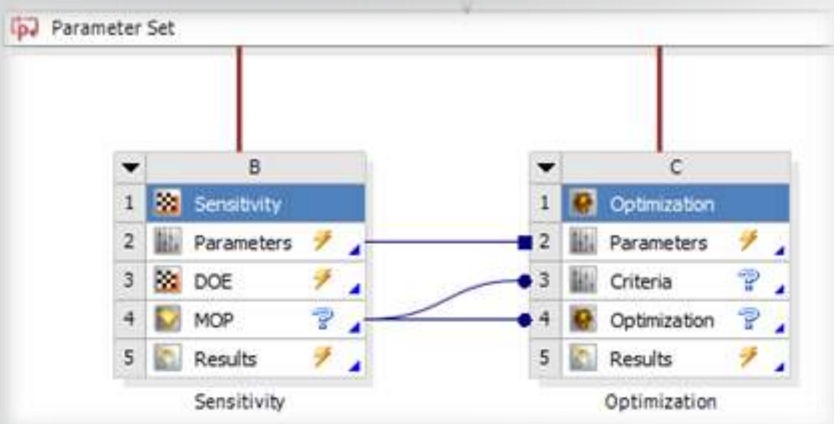
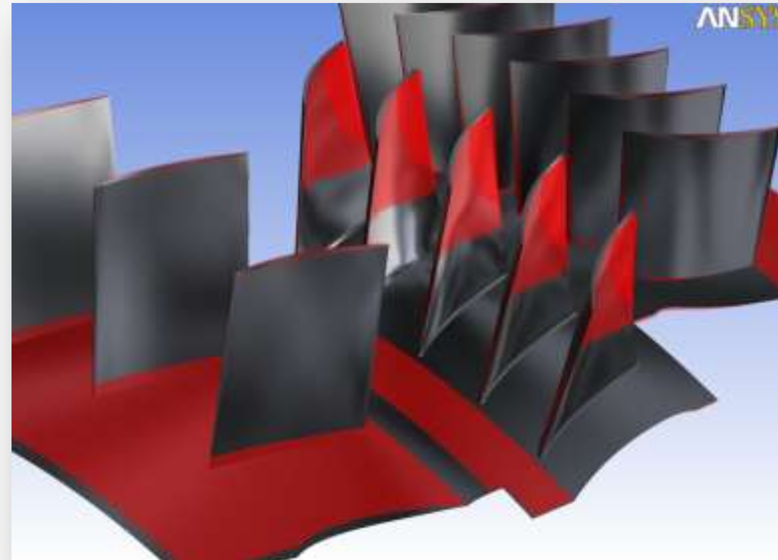
Design Optimization, Summary





	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

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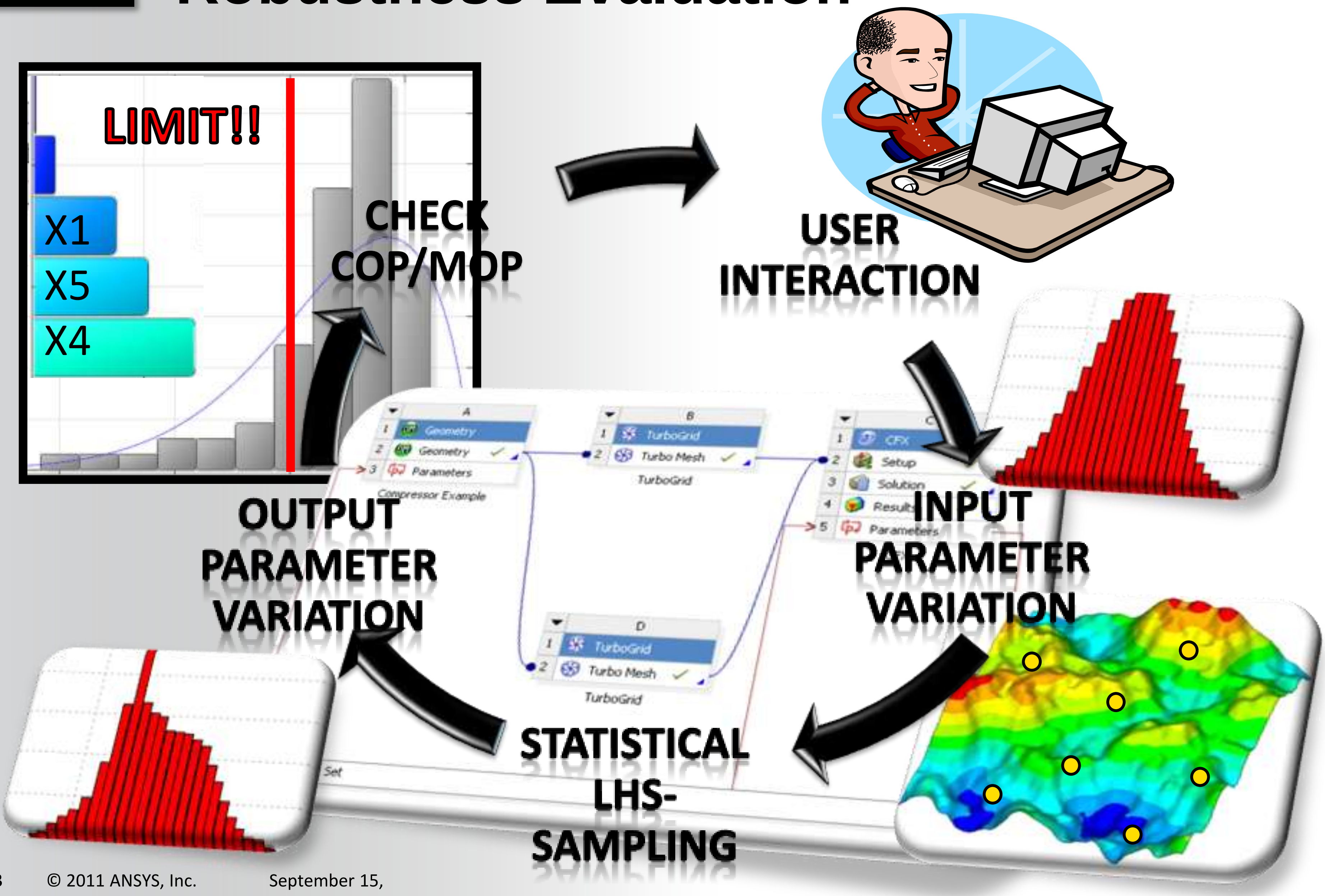
Robustness Evaluation

Robust Design??



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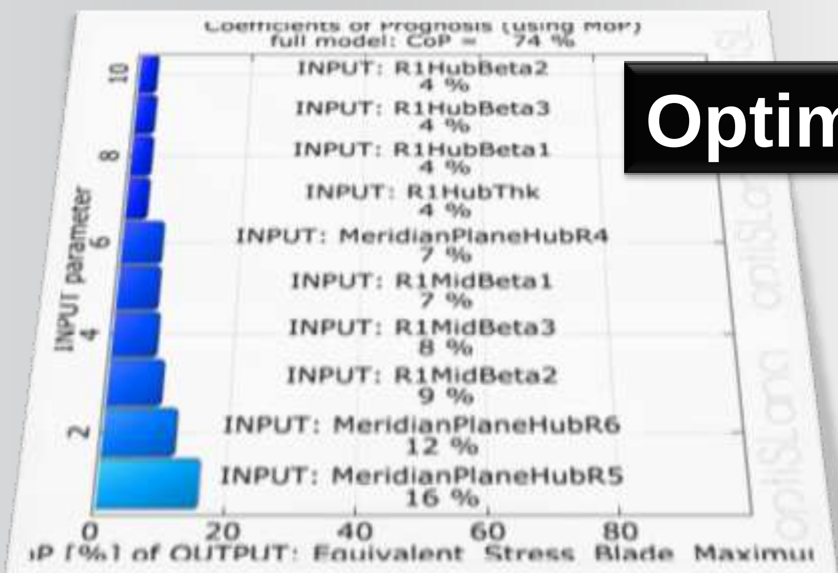
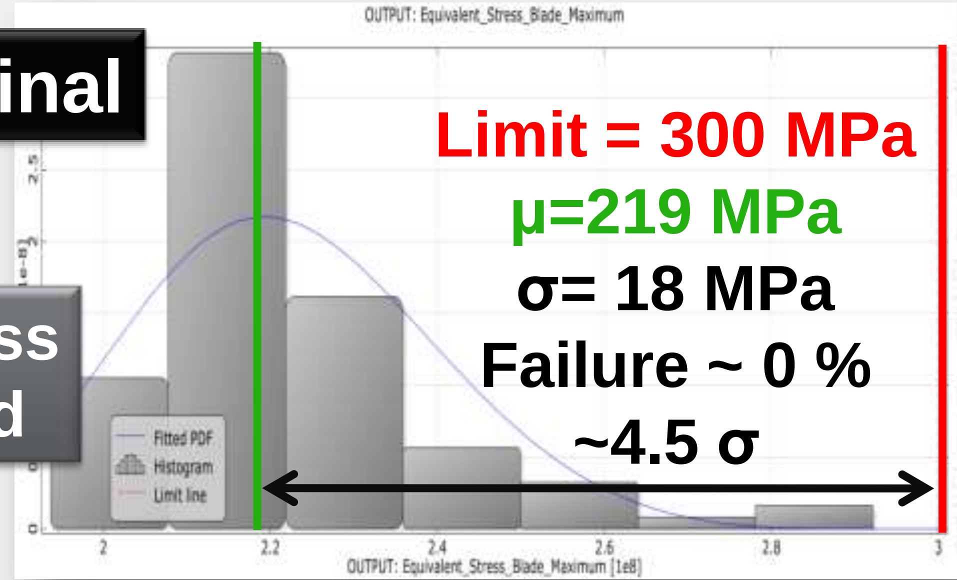
Robustness, Maximum Stress

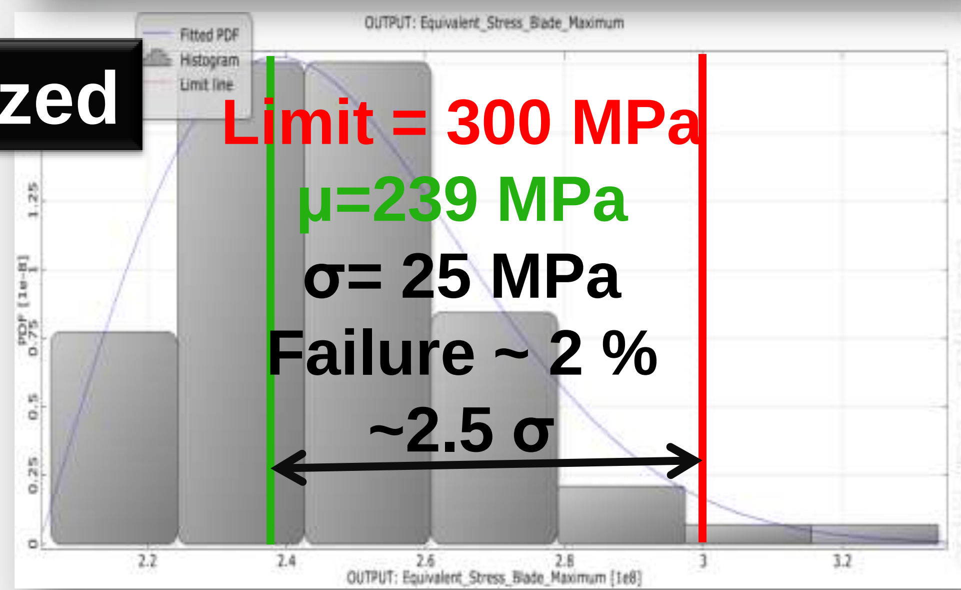


Original



Robustness decreased

Optimized



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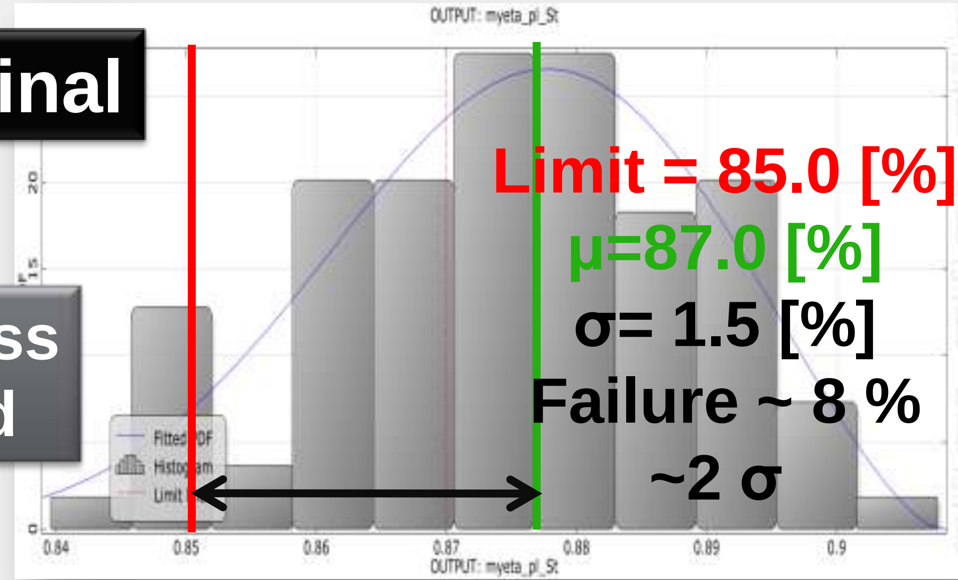
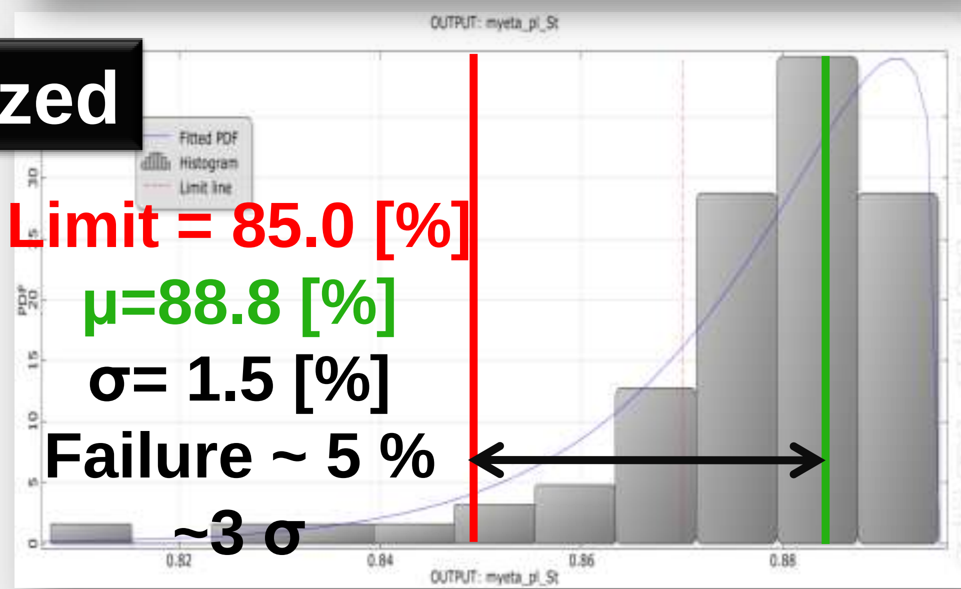
Robustness, Efficiency

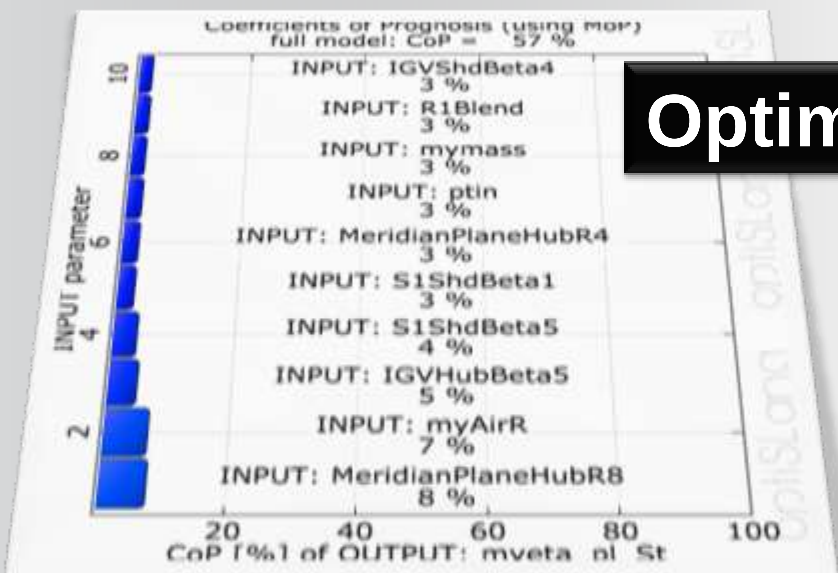
Original



Robustness increased

Optimized





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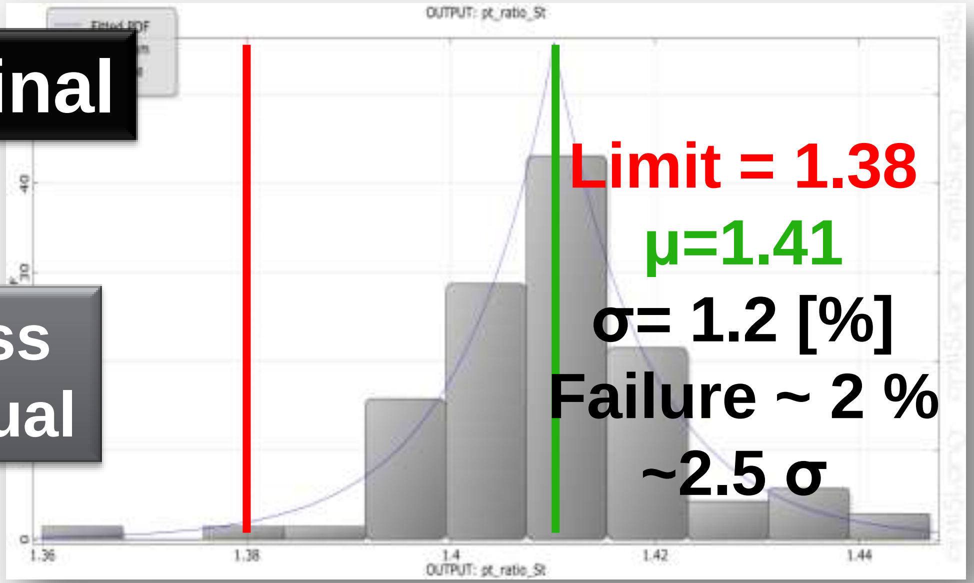
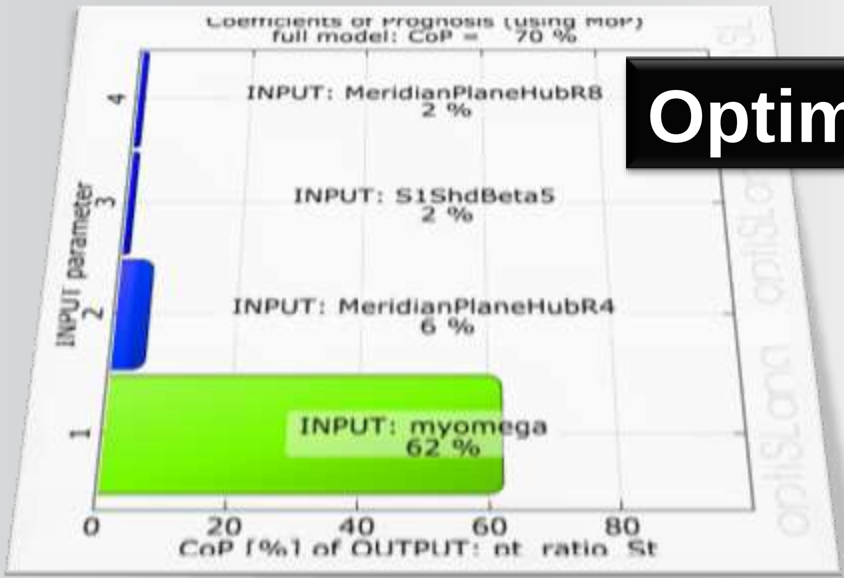
Robustness, Total Pressure Ratio

Robustness approx. equal

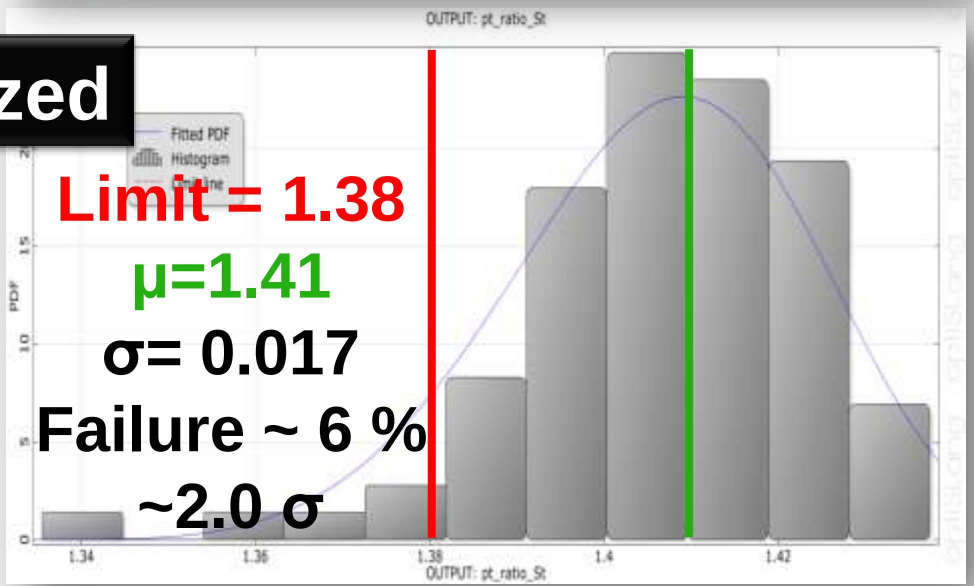
Original



Limit = 1.38
μ=1.41
σ= 1.2 [%]
Failure ~ 2 %
~2.5 σ



Optimized



Limit = 1.38
μ=1.41
σ= 0.017
Failure ~ 6 %
~2.0 σ

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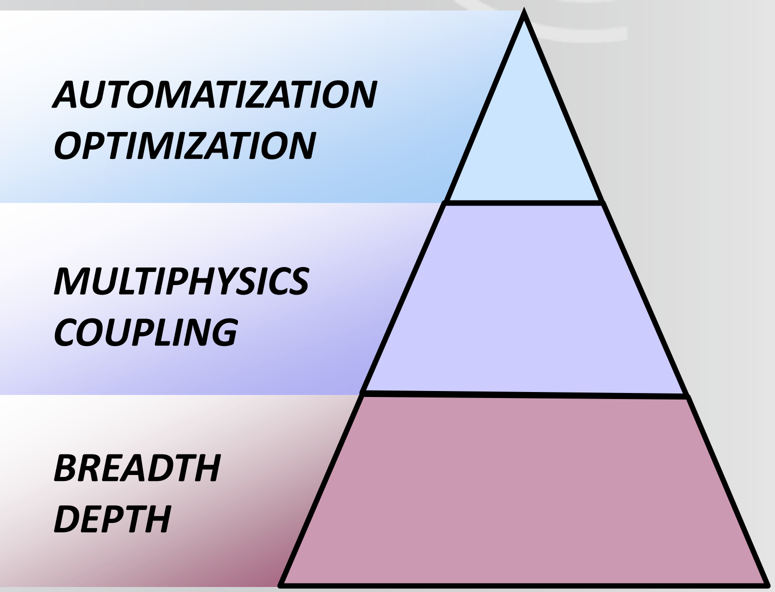
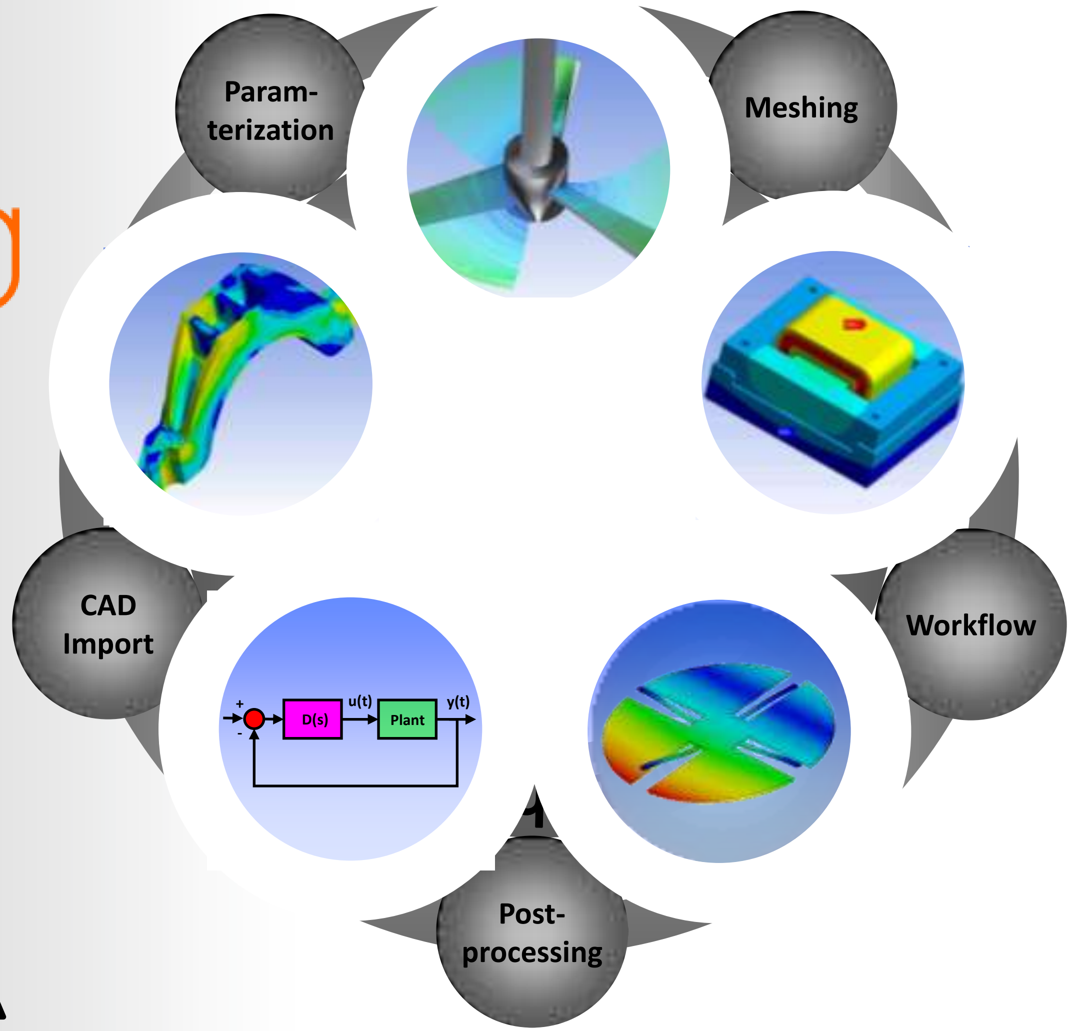
Summary





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