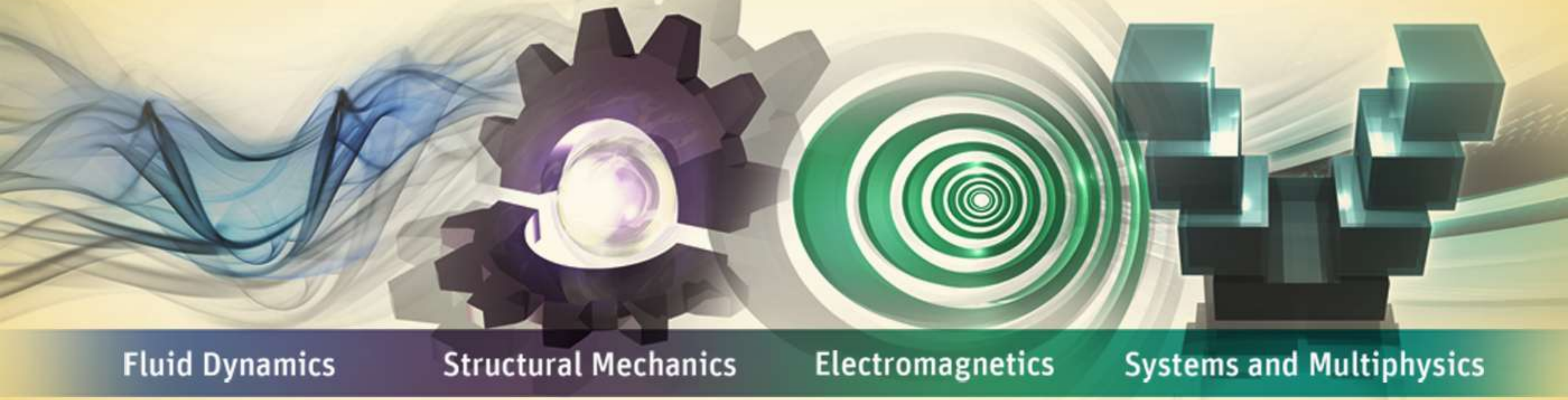
Realize Your Product Promise™

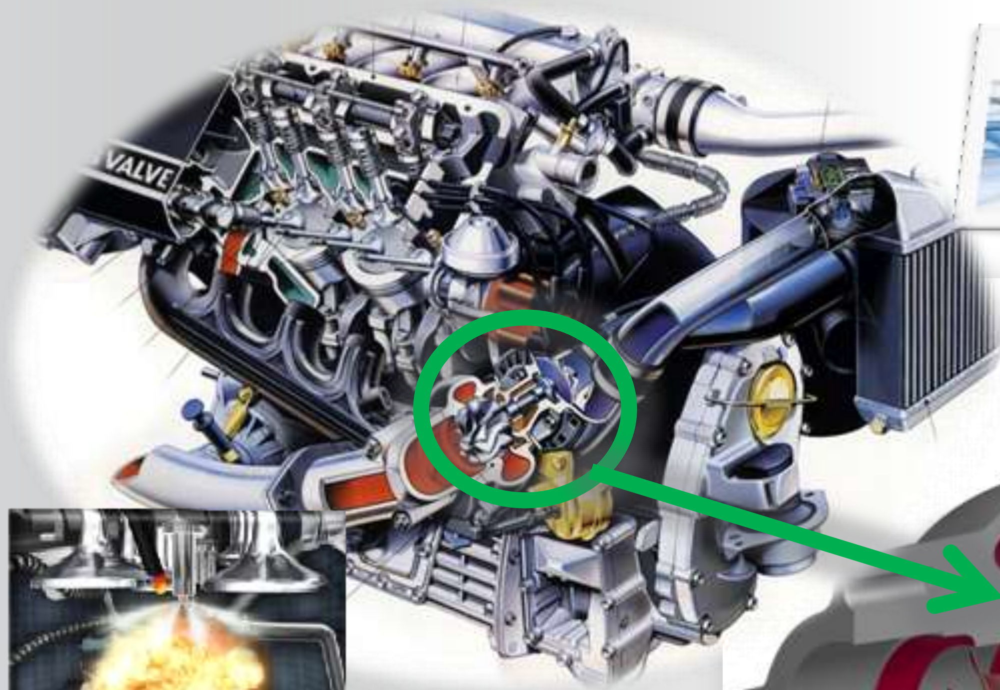
Design and Optimization of Turbo Charger Turbine Maps by Meta-Model of optimal Prognosis

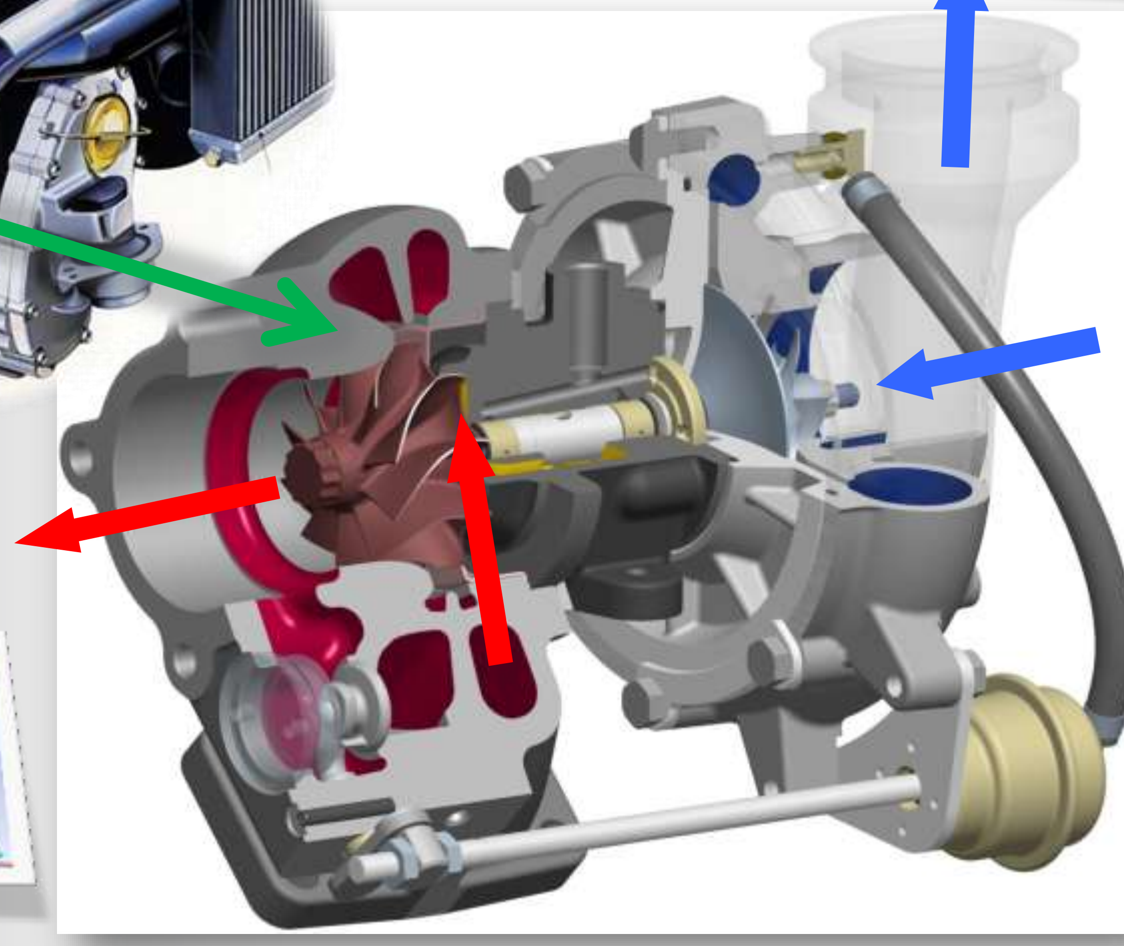


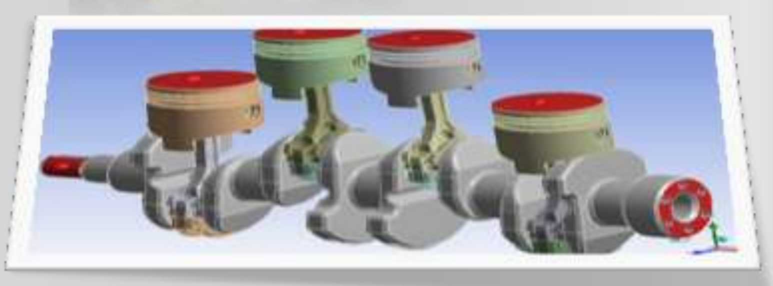
optiSLang
optimizing structural language

Johannes Einzinger
ANSYS Germany

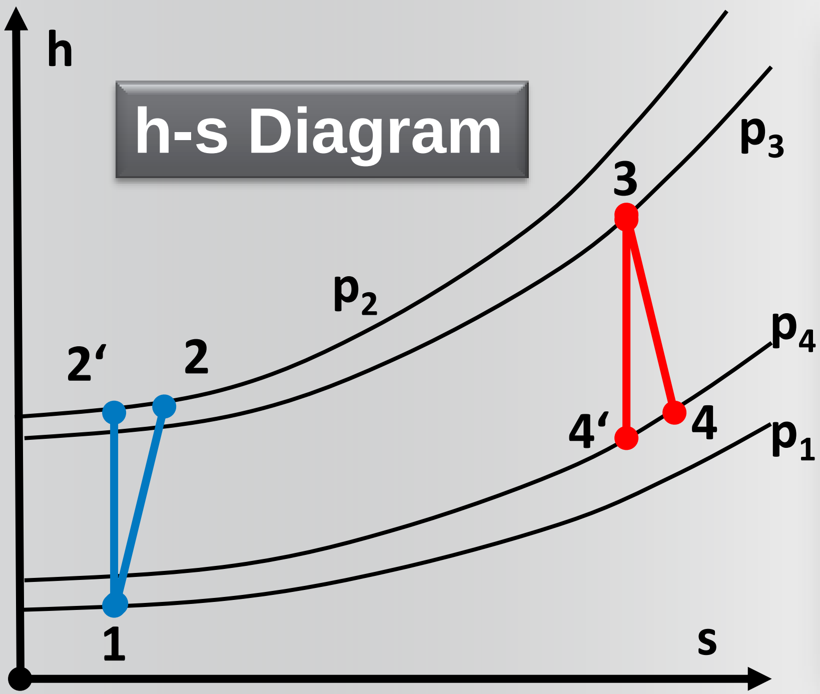
Turbo Charger, Basics

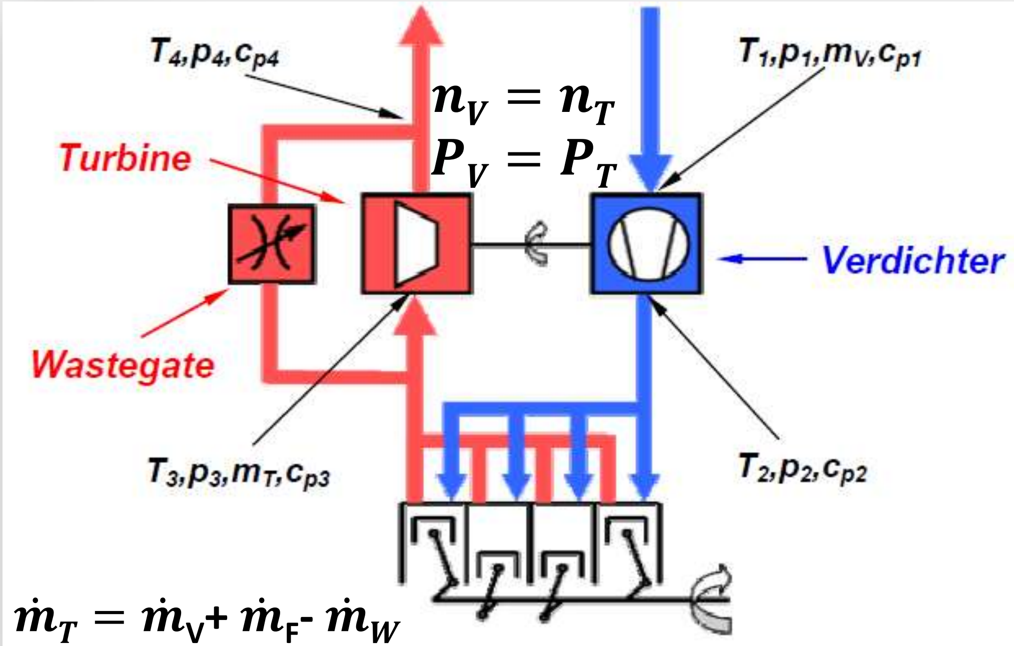






Turbo Charger, Thermodynamics





Compressor: $P_V = \frac{1}{\eta_V} \cdot \dot{m}_V \cdot \Delta h_{is}$

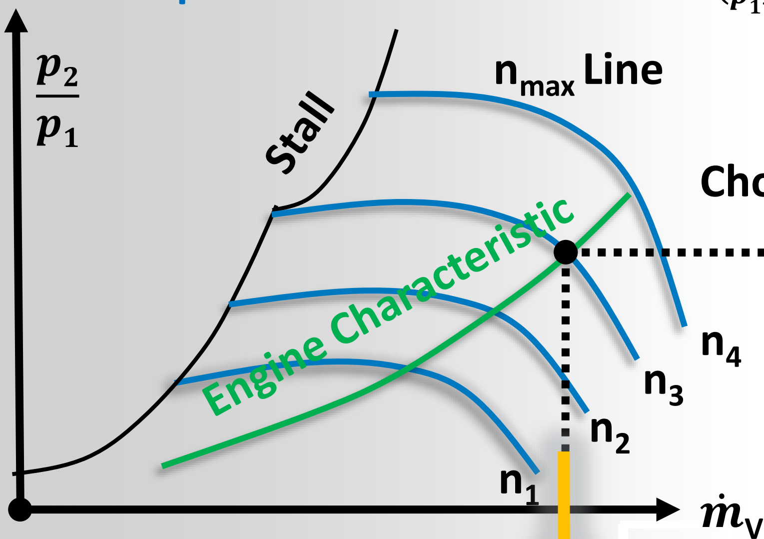
Turbine: $P_T = \eta_T \cdot \dot{m}_T \cdot \Delta h_{is}$

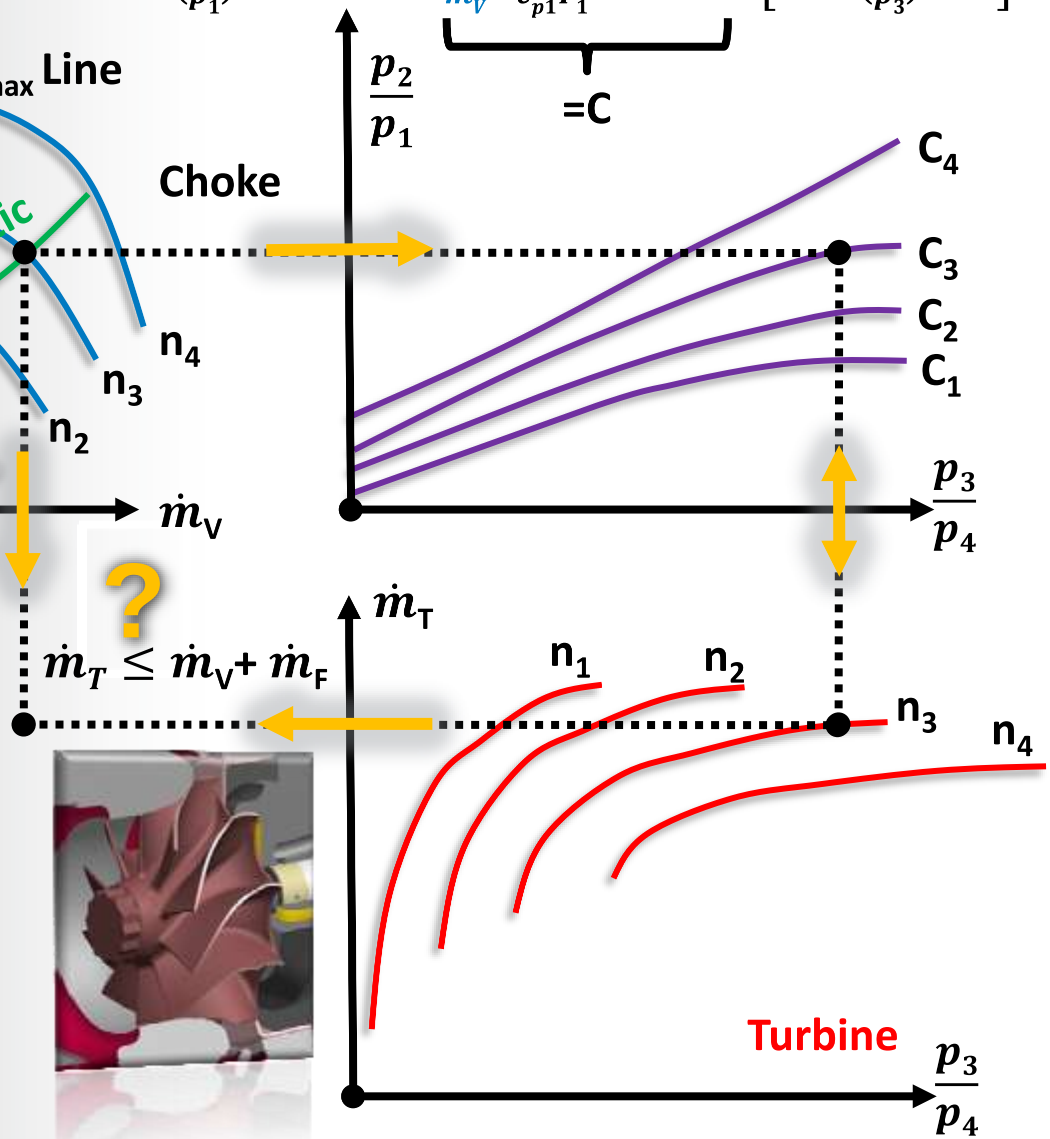
Turbo Charger Matching Equation

$$\Rightarrow \left(\frac{p_2}{p_1}\right)^{\frac{\kappa_V - 1}{\kappa_V}} = 1 + \frac{\dot{m}_T}{\dot{m}_V} \cdot \frac{c_{p3} T_3}{c_{p1} T_1} \cdot \eta_V \cdot \eta_T \cdot \left[1 - \left(\frac{p_4}{p_3}\right)^{\frac{\kappa_T - 1}{\kappa_T}}\right]$$

Turbo Charger, Matching

$$\left(\frac{p_2}{p_1}\right)^{\frac{\kappa_V-1}{\kappa_V}} = 1 + \underbrace{\frac{\dot m_T}{\dot m_V}\cdot\frac{c_{p3}T_3}{c_{p1}T_1}\cdot\eta_V\cdot\eta_T}_{=C}\cdot\left[1-\left(\frac{p_4}{p_3}\right)^{\frac{\kappa_T-1}{\kappa_T}}\right]$$





- Compressor Map must fit Engine Characteristic → m_V, η_V, n, Π_V
- Matching → Π_T wrt C
- Turbine Map → m_T, η_T
- Check / Iterate C
- Does Mass Flow match?

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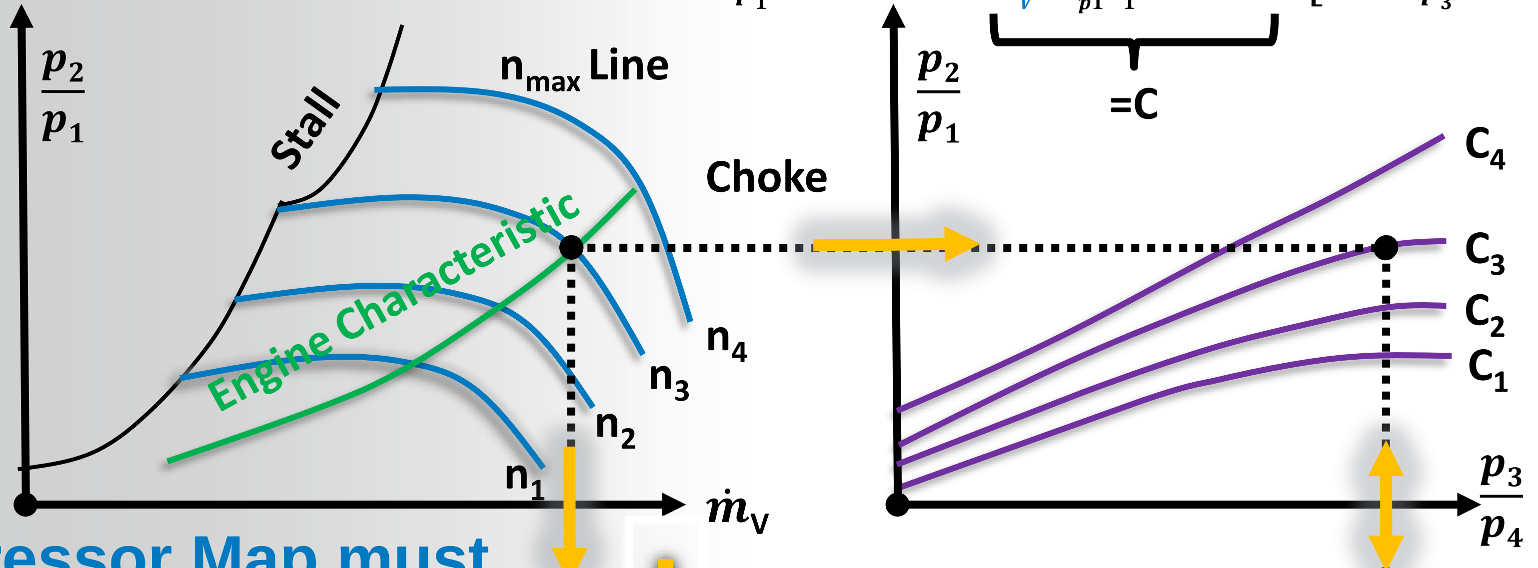
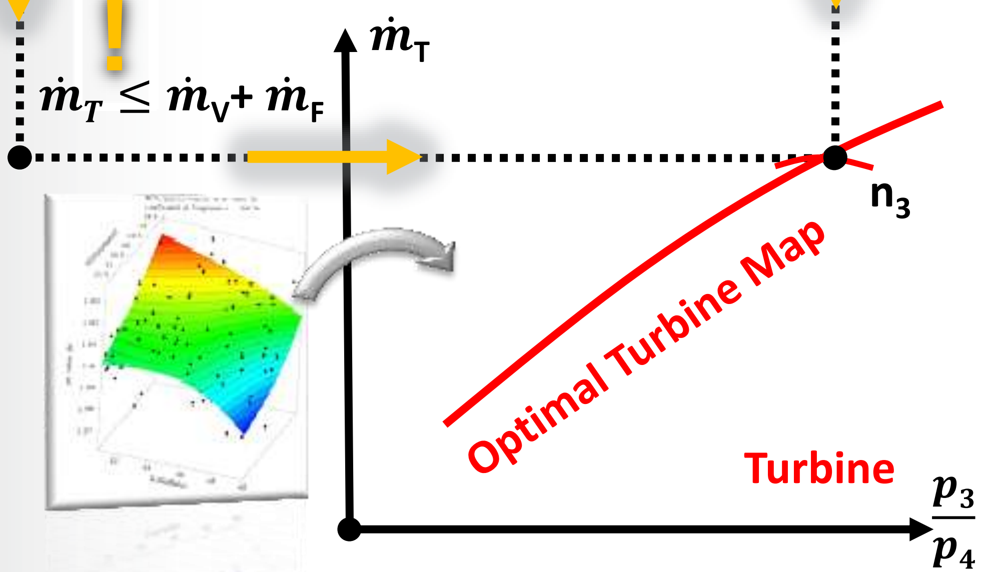
Matching by Turbine Meta-Model

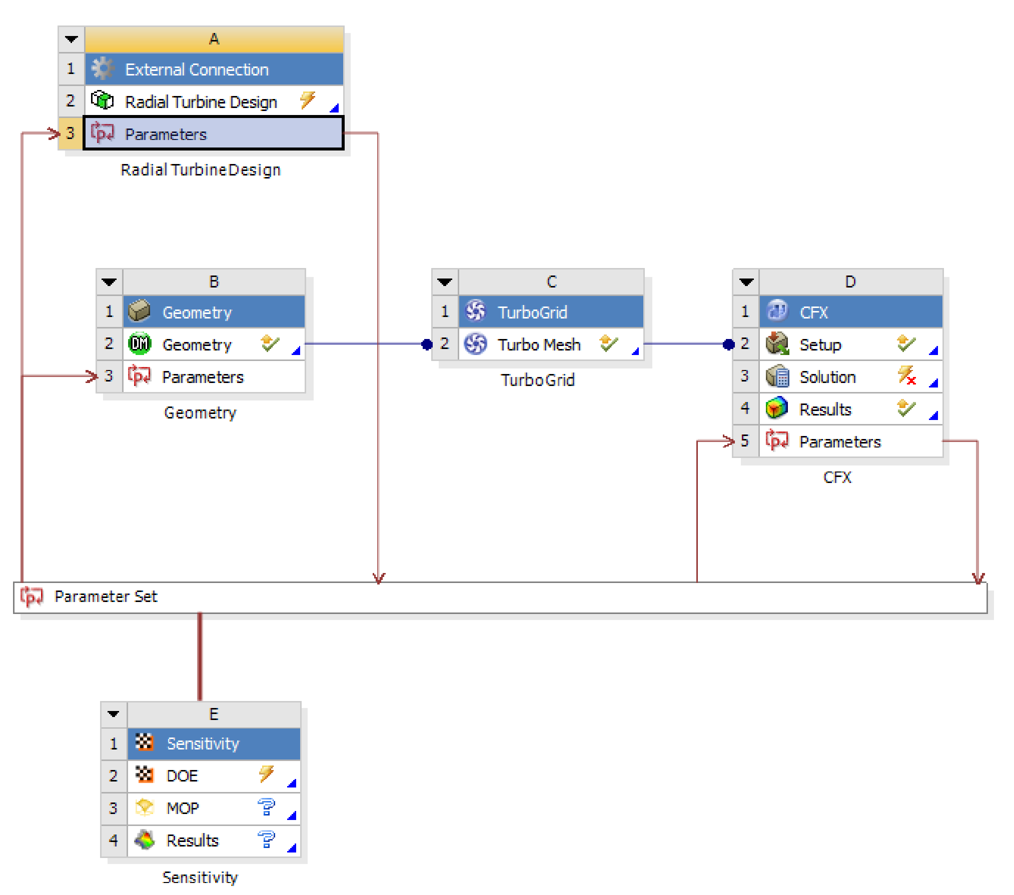
$$\left(\frac{p_2}{p_1}\right)^{\frac{\kappa_V-1}{\kappa_V}} = 1 + \underbrace{\frac{\dot m_T}{\dot m_V}\cdot\frac{c_{p3}T_3}{c_{p1}T_1}\cdot\eta_V\cdot\eta_T}_{=C}\cdot\left[1-\left(\frac{p_4}{p_3}\right)^{\frac{\kappa_T-1}{\kappa_T}}\right]$$



- Compressor Map must fit Engine Characteristic $\rightarrow m_V, \eta_V, n, \Pi_V$
- Turbine Map as MoP
- Required $\rightarrow m_T, \eta_T$
- Matching $\rightarrow \Pi_T$ wrt C
- $\rightarrow$Optimal Turbine Map



- PRIMARY DESIGN
- GEOMETRY
- CFD-SIMULATION
- META-MODEL



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- PRIMARY DESIGN
- GEOMETRY
- CFD-SIMULATION
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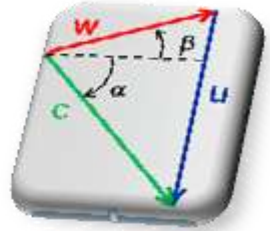
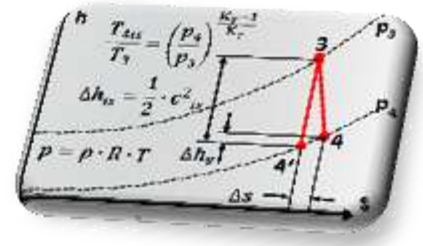
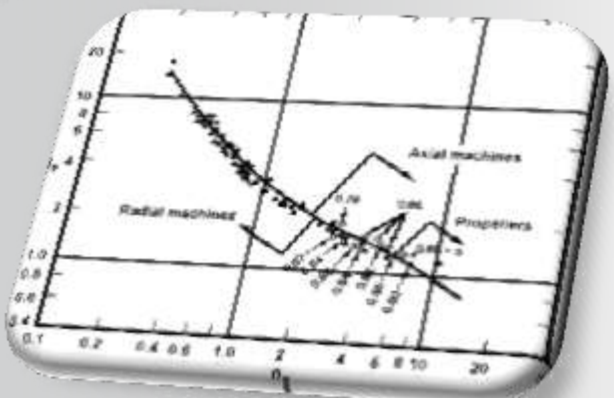
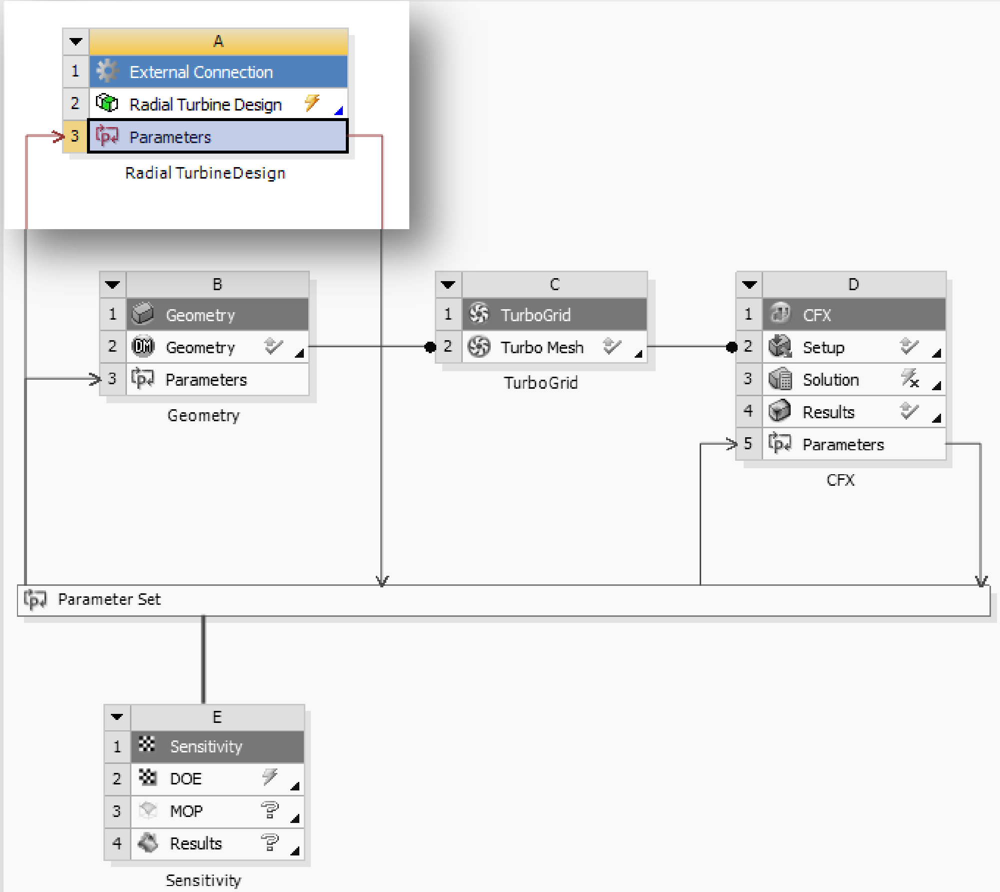


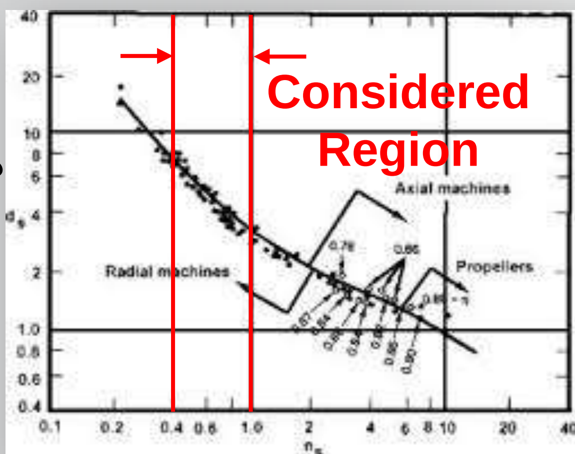


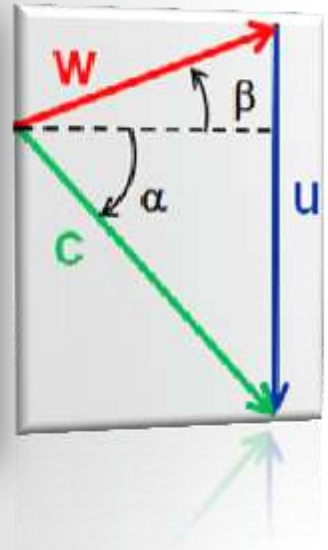


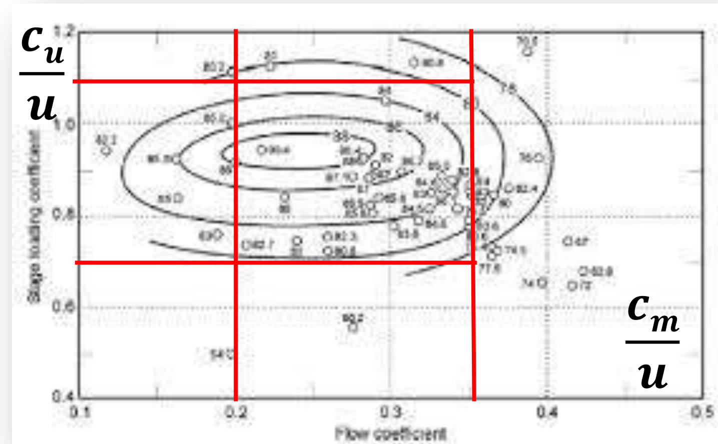


Turbine Design

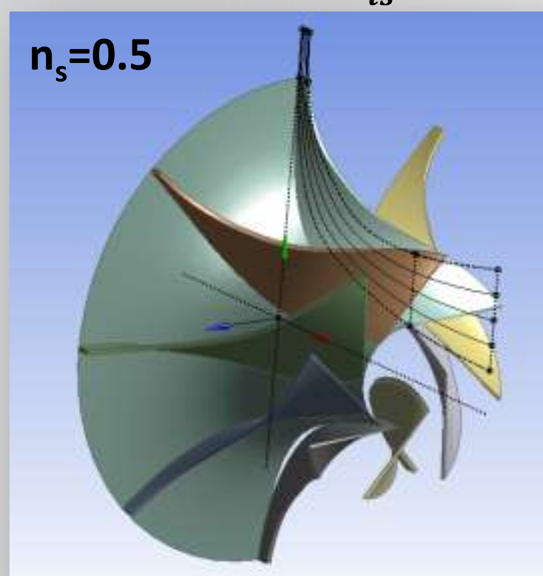
$$d_s = d \cdot \frac{\Delta h_{is}^{0.25}}{Q^{0.5}}$$

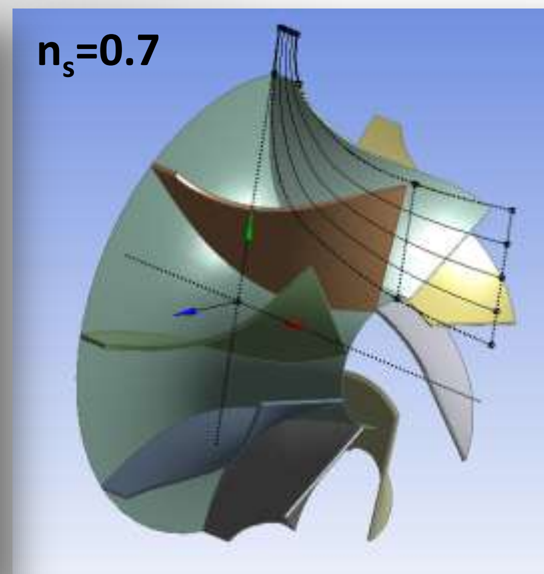


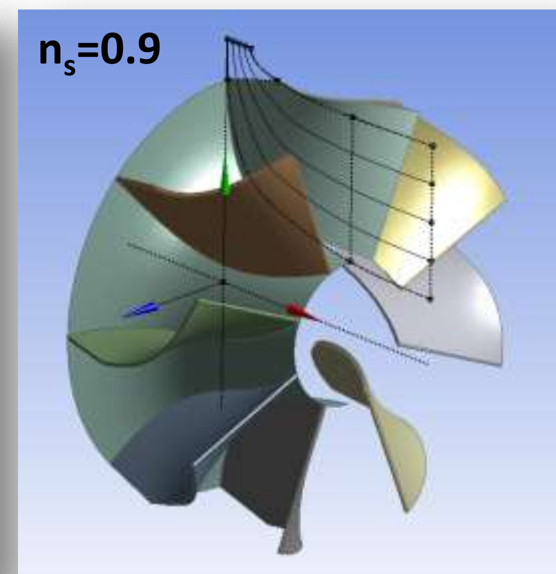




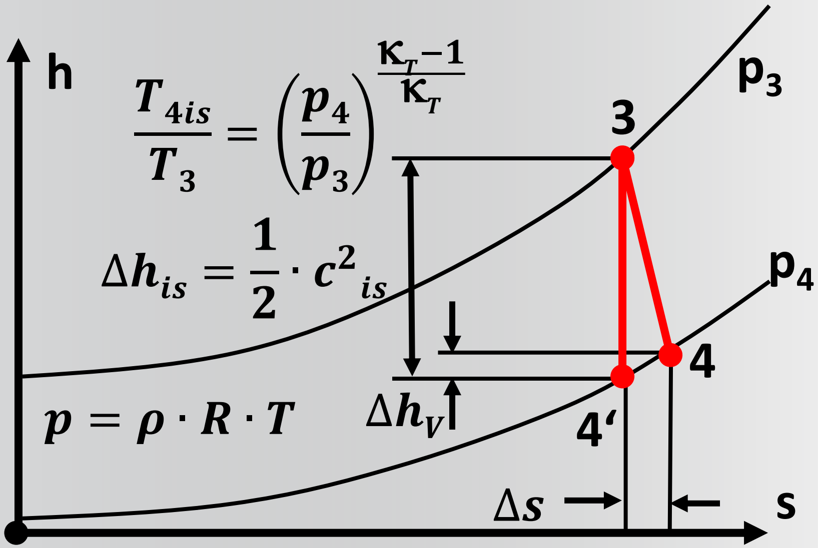
$$n_s = n \cdot \frac{Q^{0.5}}{\Delta h_{is}^{0.75}}$$

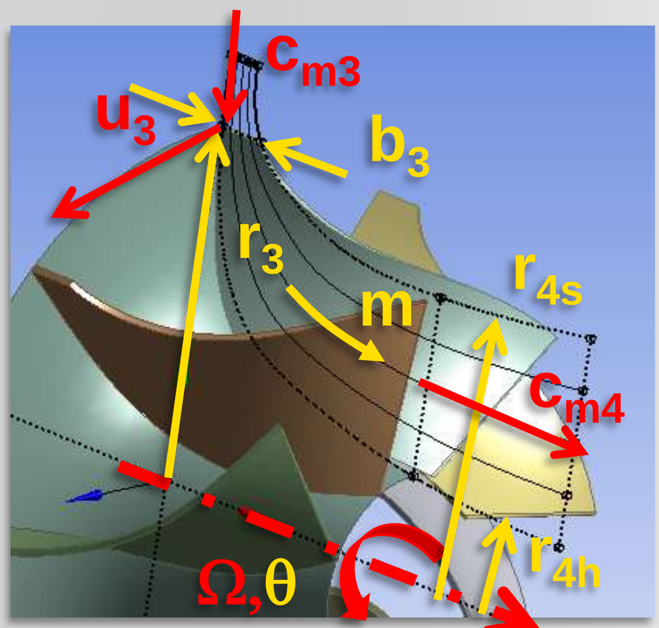






Meridian Plane





Defined Parameters:

Rotational Speed: Ω

Pressure Ratio: $\frac{p_{t3}}{p_4} \rightarrow \Delta h_{is} \rightarrow c_{is}$

Velocity Ratio: $\frac{u_3}{c_{is}} \rightarrow u_3 \rightarrow r_3$

Velocity Ratio: $\frac{c_{m4}}{u_3} \rightarrow c_{m4}$

Specific Speed: $n_s = n \cdot \frac{Q^{0.5}}{\Delta h_{is}{}^{0.75}} \rightarrow r_{4s} \rightarrow \dot{m}$

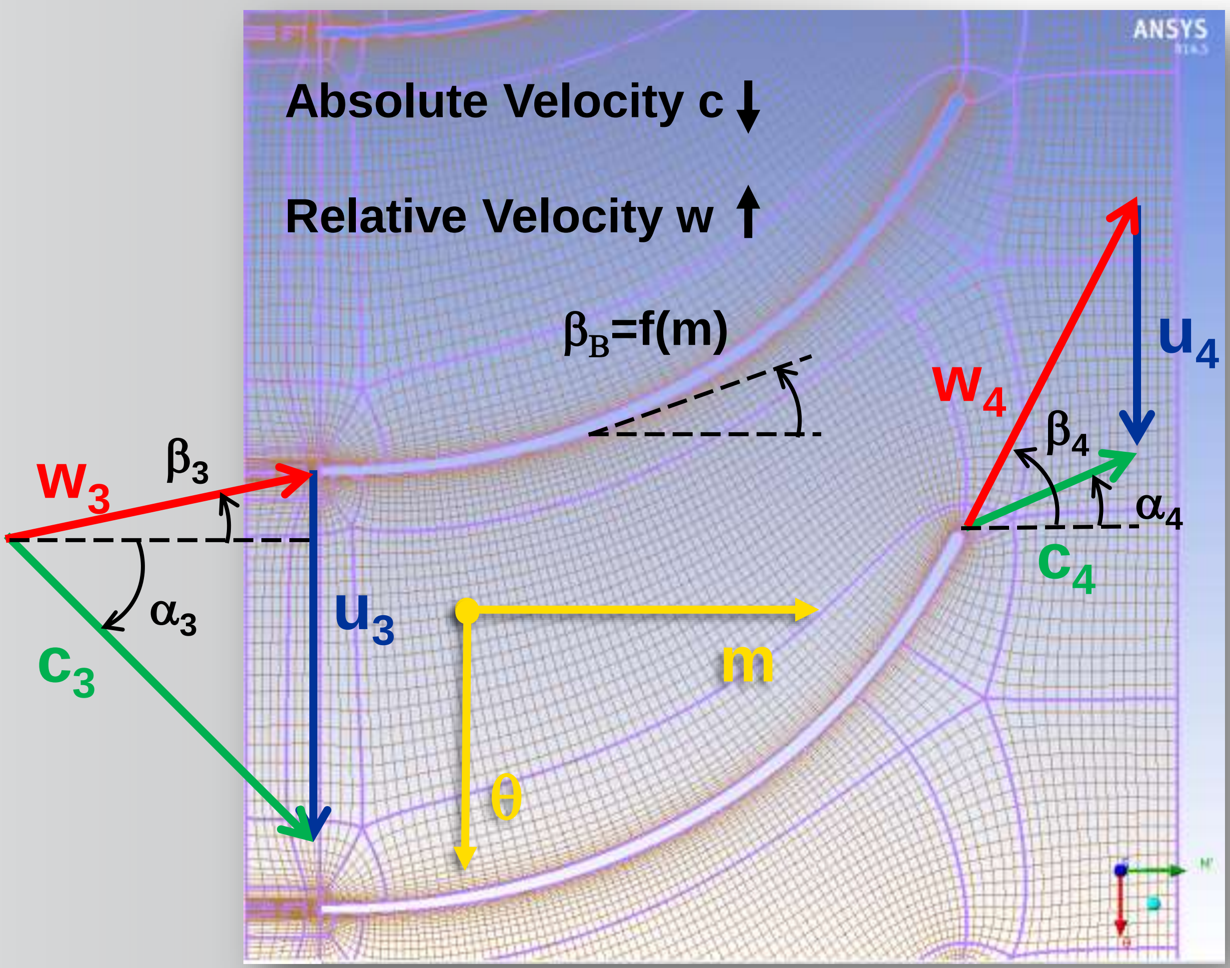
Radius Ratio: $\frac{r_{4h}}{r_{4s}} \rightarrow r_{4h}, u_{4h}, u_{4s}$

Loss Coefficient: $\Delta h_V = 0.5 \cdot \zeta \cdot c_{m4}{}^2$

Height: $\dot{m} = 2 \cdot \pi \cdot r \cdot b \cdot \rho \cdot c_{m3}$

Entropy Gain: $\Delta s = c_p \cdot ln\left(\frac{T_4}{T_3}\right) - R \cdot ln\left(\frac{p_4}{p_3}\right)$

Blade to Blade



Euler Equation

$\Delta h_t = \Delta(u \cdot c_u)$

Total Enthalpy stn Frame

$h_t = h + 0.5 \cdot c^2$

Total Enthalpy rel Frame

$h_t' = h + 0.5 \cdot w^2$

Inlet:

$\alpha_3, u_3, \beta_3 \approx \beta_{B3} \rightarrow c_3, w_3$

Outlet:

$\alpha_4 = 0, c_{m4}, u_4 \rightarrow c_4, w_4, \beta_4$

Design Parameters

Output Parameter will be compared with CFD Result → Correlation

Input Parameter

#	Name	Value	Ref.Value	Lower Bound	Upper Bound
1	LossCoefficientW	4.0	4.0	3.5	4.5
2	NumberBlades	7.0 8.0 9.0 10.0 11.0	8.0	-	-
3	RatioR3H_R3S	0.3	0.3	0.25	0.35
4	SpecificSpeed	0.7	0.7	0.4	1.0
5	RatioU2_CIS	0.7	0.7	0.5	0.9
6	RatioCM3_U2	0.25	0.25	0.2	0.35
7	OutletPressure	200000.0	200000.0	100000.0	250000.0
8	BetaB2	0.0	0.0	-30.0	0.0
9	Alpha2	65.0	65.0	45.0	75.0

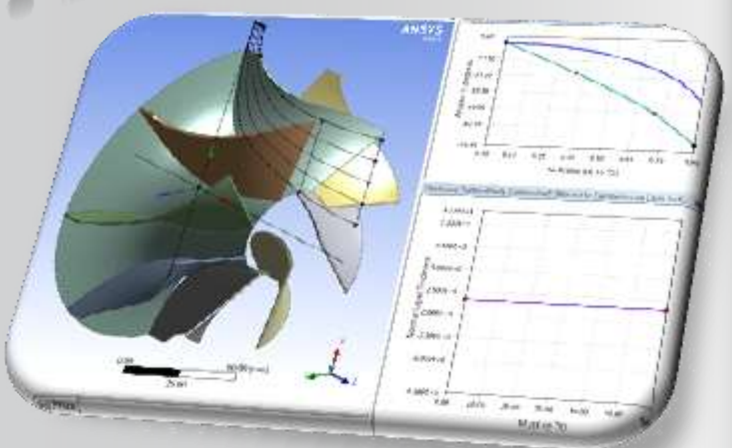
Constants

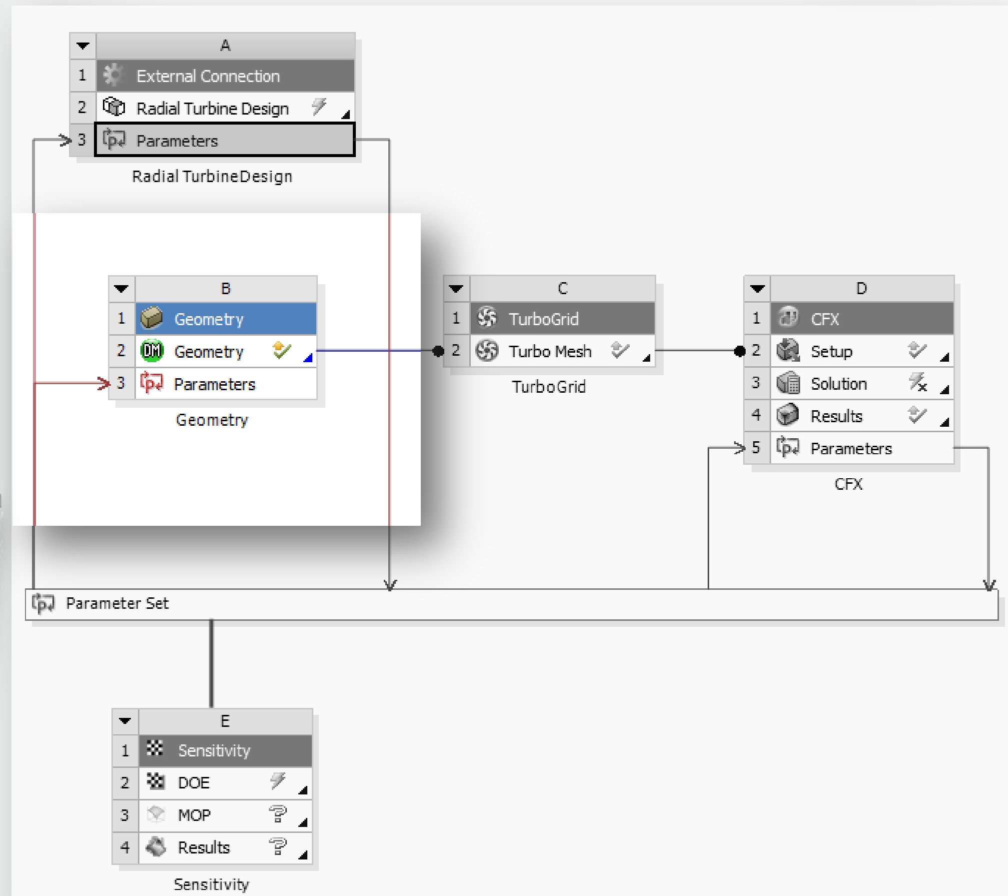
25	InletTotalTemerature	1000.0	1000.0	900.0	1100.0
26	InletTotalPressure	400000.0	400000.0	360000.0	440000.00000000006
27	GasConstantR	287.0	287.0	258.3	315.70000000000005
28	SpecificHeatCP	1004.0	1004.0	903.6	1104.4
29	RotVelocity	50000.0	50000.0	45000.0	55000.00000000001

Output Parameter

Name
MachNumberRel2
MachNumberAbs2
MachNumberRel3
MachNumberAbs3
VelocityC02
VelocityW02
VelocityU02
VelocityC03
VelocityW03
VelocityU03
InletRadius
InletHight
RadiusHub3
RadiusShd3
SpecificDiameter
MassFlowRate
ReducedMassFlow
TotalPressureRatio
TotalTemperatureRatio
EfficiencyPolytrop
EfficiencyIsentrop
EntropyGain
StaticPressureRatio
StaticTemperatureRatio
SpoutingVelocity
MeridianVelocity3
BladeVelocity
InletPressure
InletTemperature
OutletTemperature
OutletTotalPressure
OutletTotalTemperature
BetaB3Shd
BetaB3Hub
Entropy_Gain
MassFlow

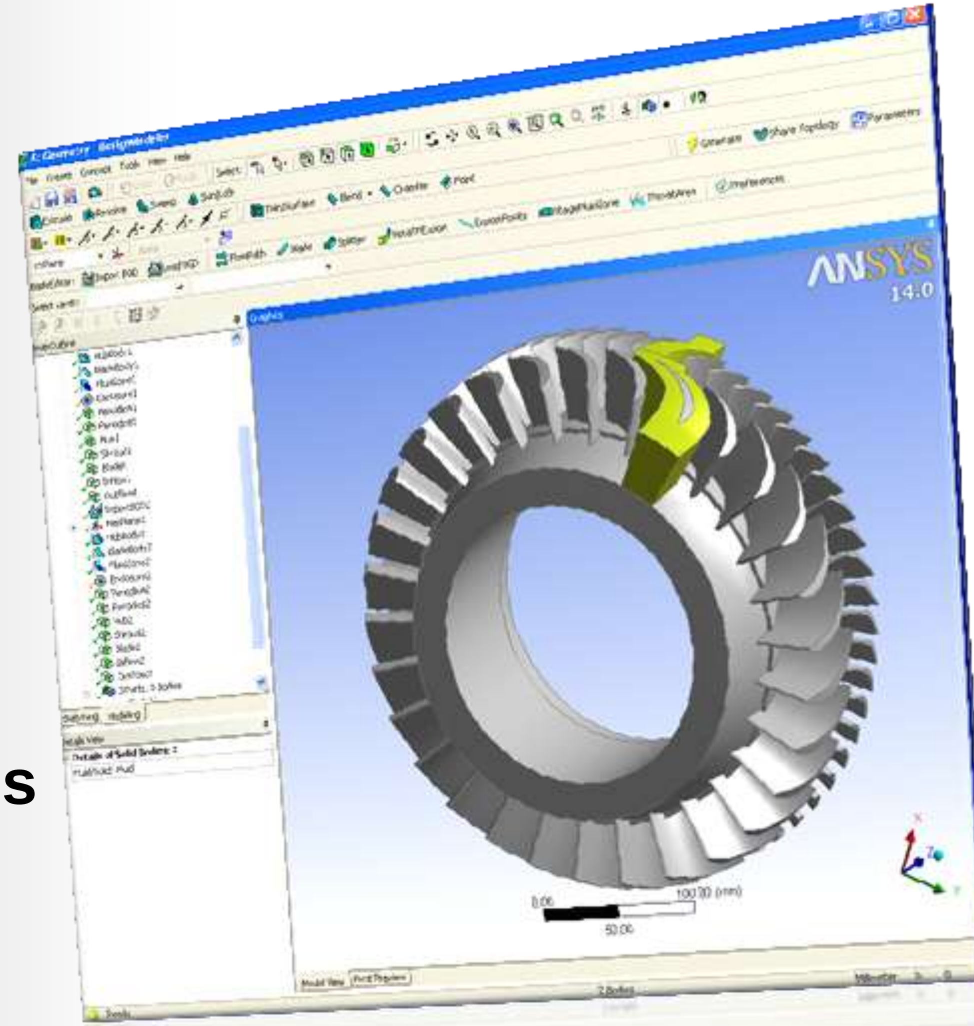
- PRIMARY DESIGN
- **GEOMETRY**
- CFD-SIMULATION
- META-MODEL





BladeModeler

- **Mean Line Design tool**
  - **Preliminary blade design**
- **Generation of 3D CAD**
- **Auto creation of**
  - **One or all blades**
  - **Hub & shroud solid**
  - **Fillets, …**
  - **Periodic fluid volumes for CFD analysis**
  - **Named selections**
- **Parametric CAD modifications**



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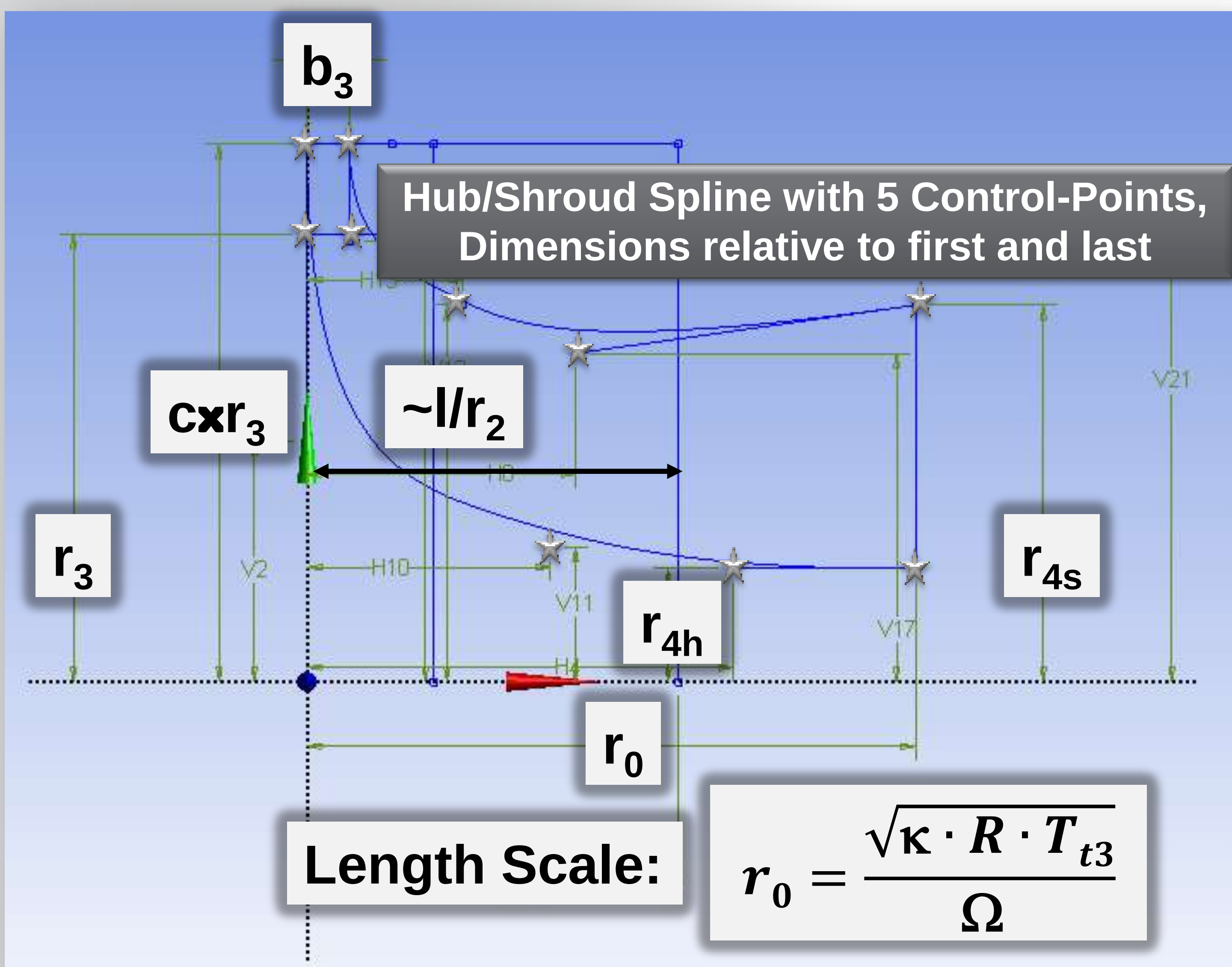
Meridian Plane



Length Scale:

$$r_0 = \frac{\sqrt{\kappa \cdot R \cdot T_{t3}}}{\Omega}$$

BM_Blades	8
BM_B2	7.5797
BM_HubZ3_Rel	0.4
BM_HubR5	20.256
BM_ShdZ3_Rel	0.2
BM_HubZ4_Rel	0.7
BM_Z5	108.97
BM_ShdR2_Rel	0.4
BM_HubR2_Rel	0.3
BM_HubR3_Rel	0.05
BM_ShdR3_Rel	0
BM_ShdR4_Rel	-0.3
BM_ShdR5	67.519
BM_R2	80.318
BM_ShdZ4_Rel	0.4
BM_R0	121.07
BM_R1	96.381
BM_HubBeta4	-45.25
BM_HubBeta1	0
BM_L2_Rel	0.55
BM_HubBeta2_Rel	0.8
BM_HubBeta3_Rel	0.4
BM_ShdBeta1	0
BM_ShdBeta4	-73.438
BM_ShdBeta2_Rel	0.7
BM_ShdBeta3_Rel	0.3
BM_R2S	80.318
BM_HubBeta4_Inc	10

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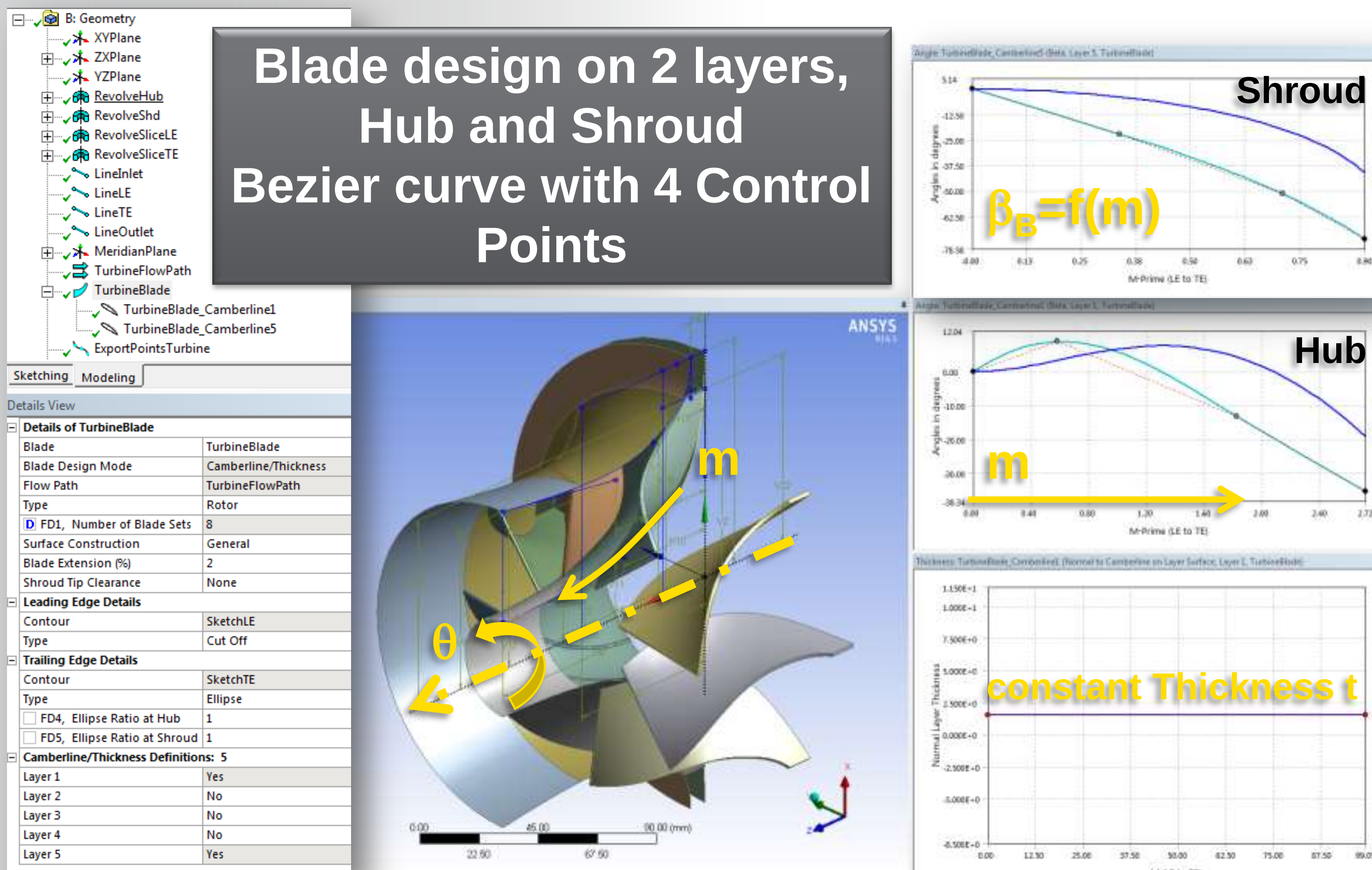
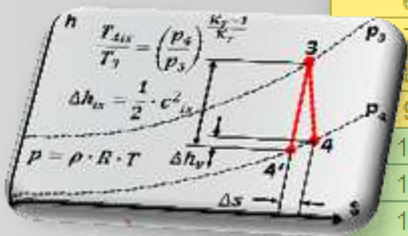
Blade to Blade



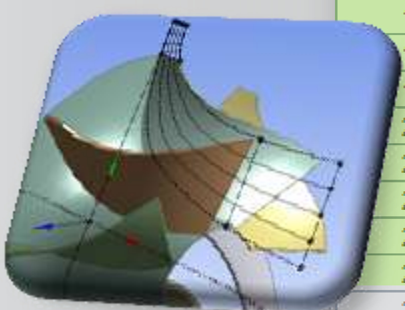
Details of TurbineBlade	
Blade	TurbineBlade
Blade Design Mode	Camberline/Thickness
Flow Path	TurbineFlowPath
Type	Rotor
D FD1, Number of Blade Sets	8
Surface Construction	General
Blade Extension (%)	2
Shroud Tip Clearance	None
Leading Edge Details	
Contour	SketchLE
Type	Cut Off
Trailing Edge Details	
Contour	SketchTE
Type	Ellipse
FD4, Ellipse Ratio at Hub	1
FD5, Ellipse Ratio at Shroud	1
Camberline/Thickness Definitions: 5	
Layer 1	Yes
Layer 2	No
Layer 3	No
Layer 4	No
Layer 5	Yes

Design Parameters

Design



Geometry



Constants

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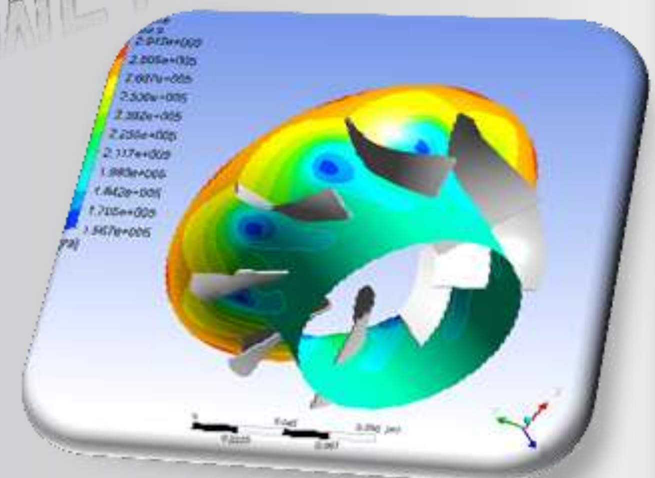
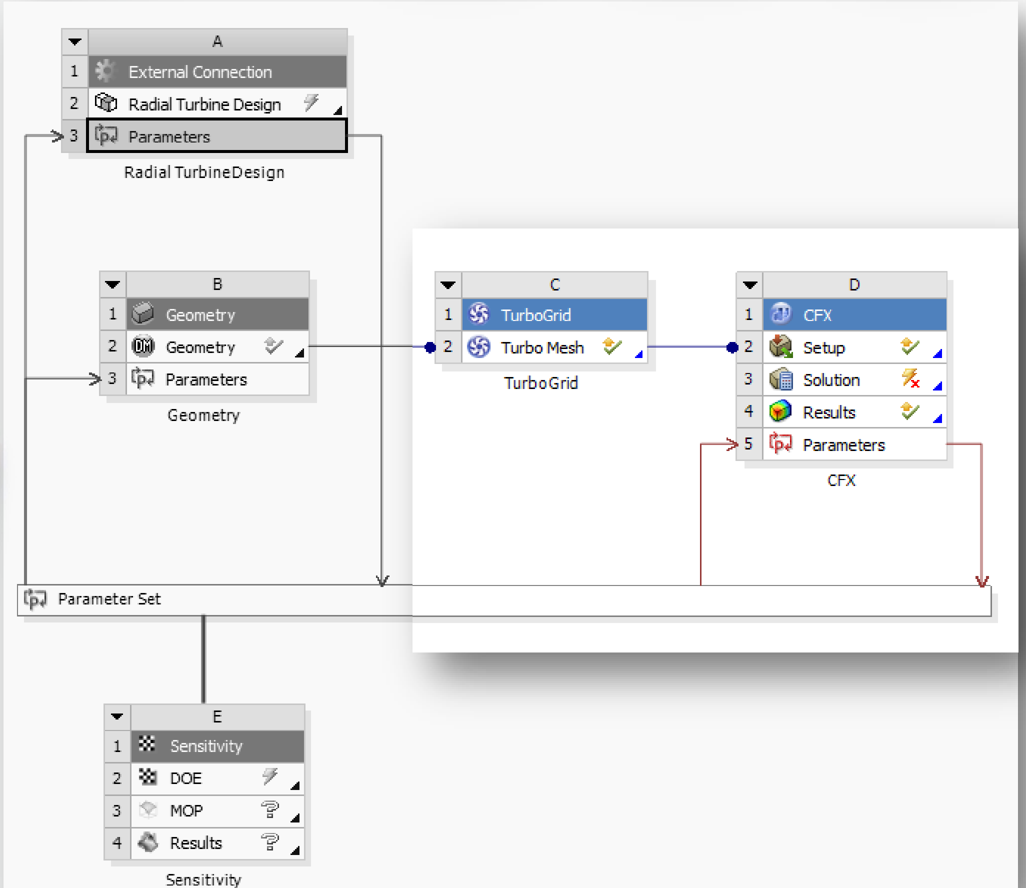
7	OutletPressure	200000.0	200000.0	100000.0	250000.0
8	BetaB2	0.0	0.0	-30.0	0.0
9	Alpha2	65.0	65.0	45.0	75.0
10	BM_HubZ3_Rel	0.4	0.4	0.325	0.5
11	BM_ShdZ3_Rel	0.2	0.2	0.1	0.25
12	BM_ShdR2_Rel	0.4	0.4	0.2	0.6
13	BM_HubR2_Rel	0.3	0.3	0.2	0.4
14	BM_HubR3_Rel	0.05	0.05	0.0	0.1
15	BM_ShdR3_Rel	0	0	-0.0	0.2
16	BM_HubZ4_Rel	0.7	0.7	0.6	0.8
17	BM_ShdR4_Rel	-0.3	-0.3	-0.4	-0.0
18	BM_ShdZ4_Rel	0.4	0.4	0.35	0.5
19	BM_L2_Rel	0.55	0.55	0.45	0.65
20	BM_HubBeta2_Rel	0.8	0.8	0.6	1.0
21	BM_HubBeta3_Rel	0.4	0.4	0.1	0.5
22	BM_ShdBeta2_Rel	0.7	0.7	0.5	1.0
23	BM_ShdBeta3_Rel	0.3	0.3	0.05	0.4
24	BM_HubBeta4_Inc	10	10	0.0	15.0
25	InletTotalTemerature	1000.0	1000.0	900.0	1100.0
26	InletTotalPressure	400000.0	400000.0	360000.0	440000.00000000006
27	GasConstantR	287.0	287.0	258.3	315.70000000000005
28	SpecificHeatCP	1004.0	1004.0	903.6	1104.4
29	RotVelocity	50000.0	50000.0	45000.0	55000.00000000001

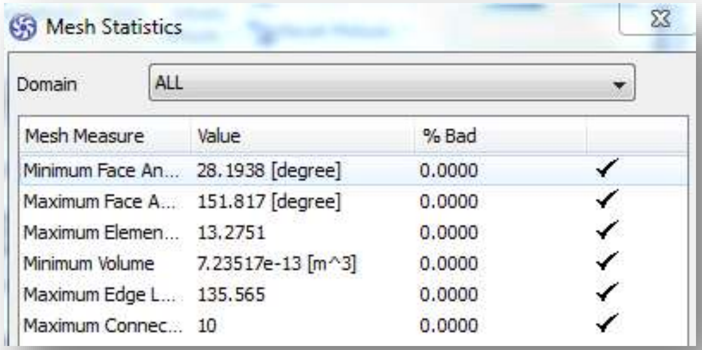
- PRIMARY DESIGN
- GEOMETRY
- CFD-SIMULATION
- META-MODEL



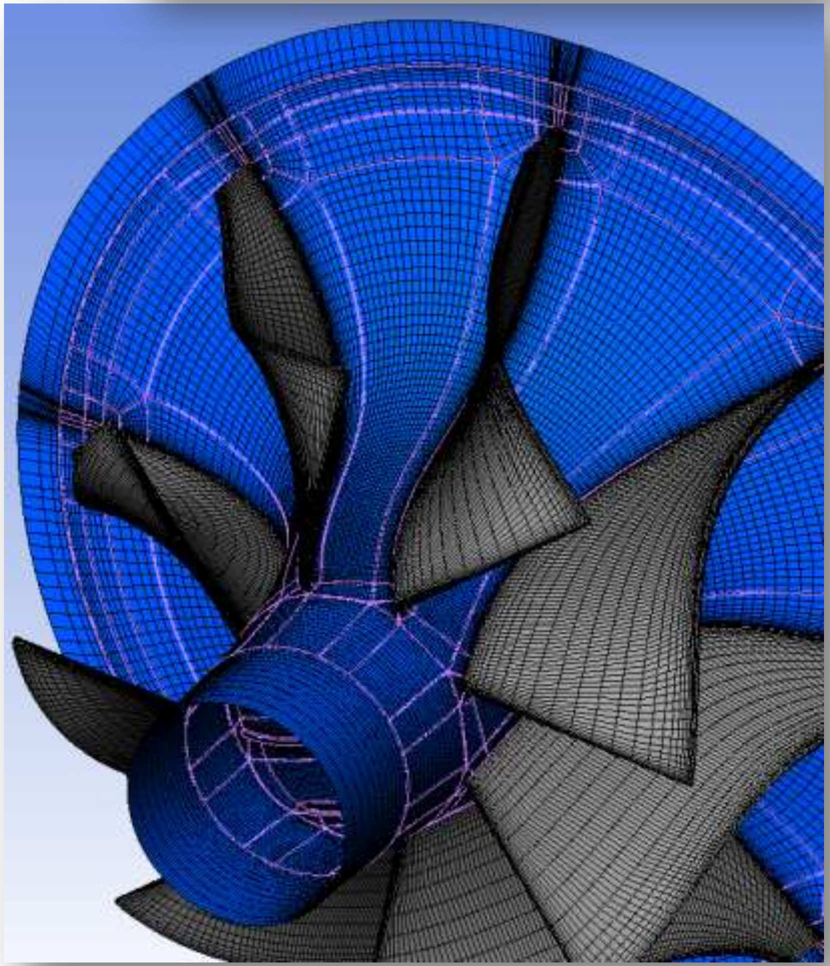


TurboGrid

- **Automated mesh generation for bladed turbo machinery components**
- **High quality hexahedral grids**
- **Repeatable**
  - **Minimize mesh influence in design comparison**
- **Scalable**
  - **Maintain quality with mesh refinement**

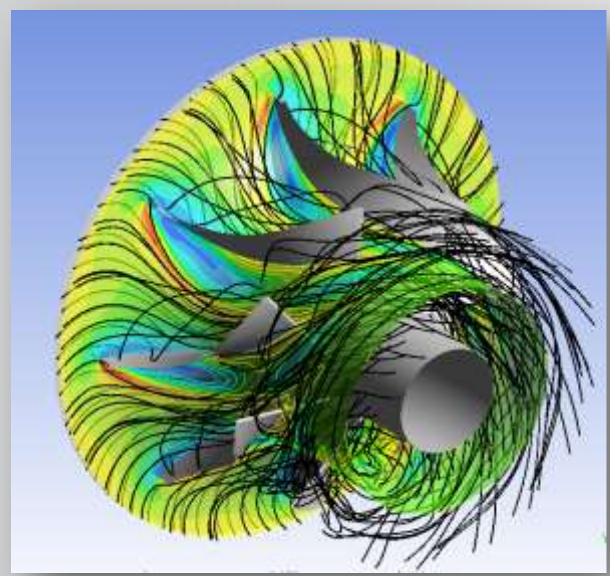


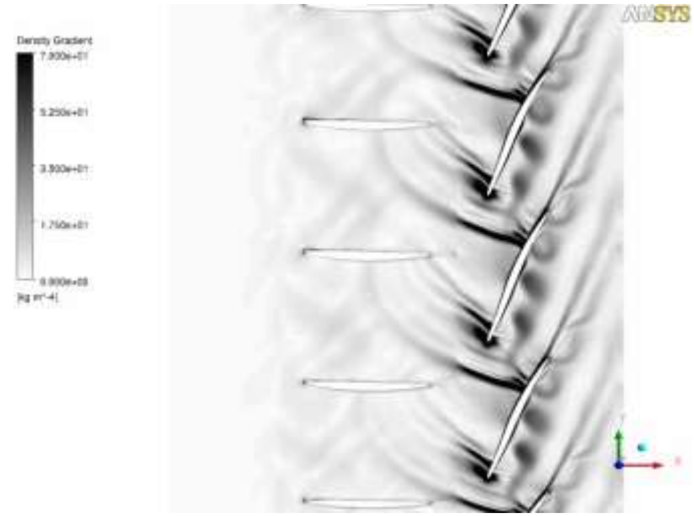
Mesh Measure	Value	% Bad	
Minimum Face An...	28.1938 [degree]	0.0000	✓
Maximum Face A...	151.817 [degree]	0.0000	✓
Maximum Elemen...	13.2751	0.0000	✓
Minimum Volume	7.23517e-13 [m^3]	0.0000	✓
Maximum Edge L...	135.565	0.0000	✓
Maximum Connec...	10	0.0000	✓



ANSYS CFX

- Fast & scalable solver
- Low speed to supersonic
- Steady/transient
- Turbulence & heat transfer
- Multiple Frame of Reference
- Multi-phase flow
- Real fluids
- Fluid/structure interaction



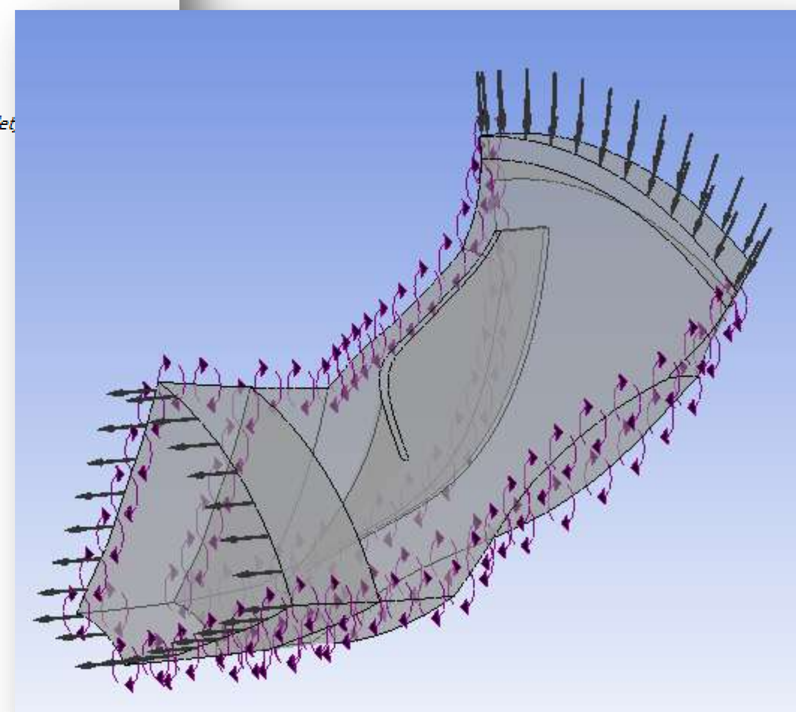


Set-Up & Boundary Conditions

Expressions

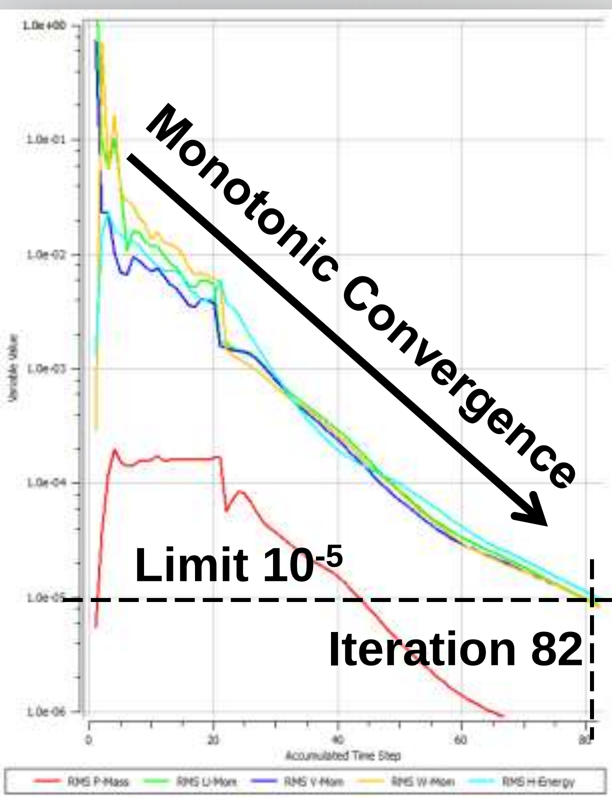
Entropy Gain	(Soutet-Sinlet)/myAirR
MassFlow	massFlow()@Inlet*nSector
Sinlet	massFlowAve(Static Entropy)@Inlet
Soutet	massFlowAve(Static Entropy)@Outlet
Tin	massFlowAve(Temperature)@Inlet
Torque	(torque_z()@Blade+torque_z()@Hub+torque_z()@Shroud)*nSector
Tout	massFlowAve(Temperature)@Outlet
Ts Ratio	Ttin/Tout
Tt Ratio	Ttin/Ttout
Ttin	726.85 [C]
Ttout	massFlowAve(Total Temperature in Stn Frame)@Outlet
U2	r Inlet*myomega/1[rad]
U2 cis	U2/c is
aitern0	20
aitern1	100
aitern2	200
alpha in	1.1344640137935 [radian]
c is	sqrt(2*max((massFlowAve(Total Enthalpy in Stn Frame)@Inlet-massFlowAve(Static Enthalpy)@Outlet
c m	massFlowAve(Velocity w)@Outlet
cm U2	c m/U2
myAirCP	1004 [J kg^-1 C^-1]
myAirCV	myAirCP-myAirR
myAirDensity	R/myAirR
myAirR	287 [J kg^-1 C^-1]
myeta is ts	(1-1/Tt Ratio)/max((1-((1/max(ps Ratio,1.01))^((mykappa-1)/mykappa))),0.01)
myeta is tt	(1-1/Tt Ratio)/max((1-((1/max(pt Ratio,1.01))^((mykappa-1)/mykappa))),0.01)
myeta pl ts	ln(1/Tt Ratio) / min(ln((1/max(ps Ratio,1.01))^((mykappa-1)/mykappa)),-0.01)
myeta pl tt	ln(1/Tt Ratio) /min(ln((1/max(pt Ratio,1.01))^((mykappa-1)/mykappa)),-0.01)
mykappa	myAirCP/myAirCV
myomega	5235.9877558333328 [radian s^-1]
nSector	8
pin	massFlowAve(Pressure)@Outlet
pout	200000 [Pa]
poutlet	pout+(1-ramp)*(ptin-pout)
ps Ratio	ptin/pout
pt Ratio	ptin/ptout
ptin	400000 [Pa]
ptout	massFlowAve(Total Pressure in Stn Frame)@Outlet
r Inlet	0.0803175295488 [m]

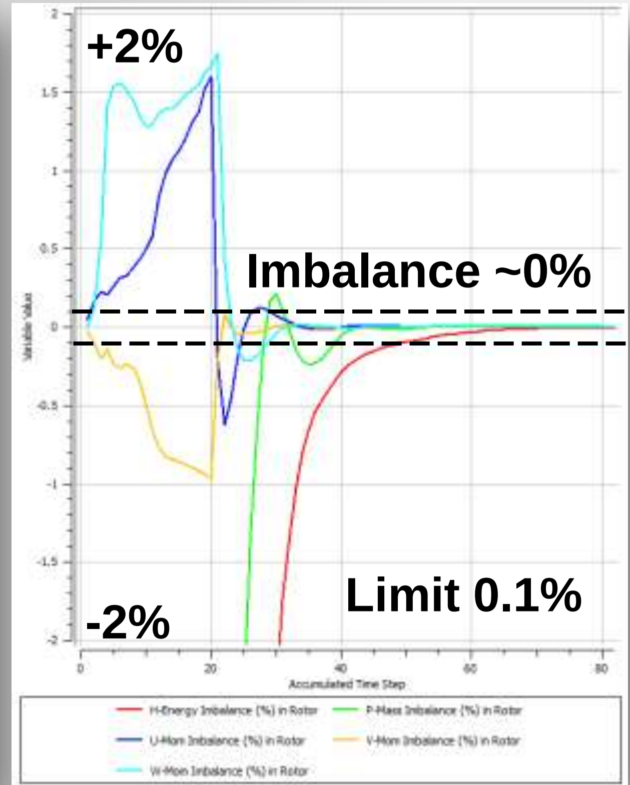
Fluid ideal Gas
Turbulence Model SST
Total Pressure and Temperature @ Inlet
Static Pressure @ Outlet
Relative Frame of Reference

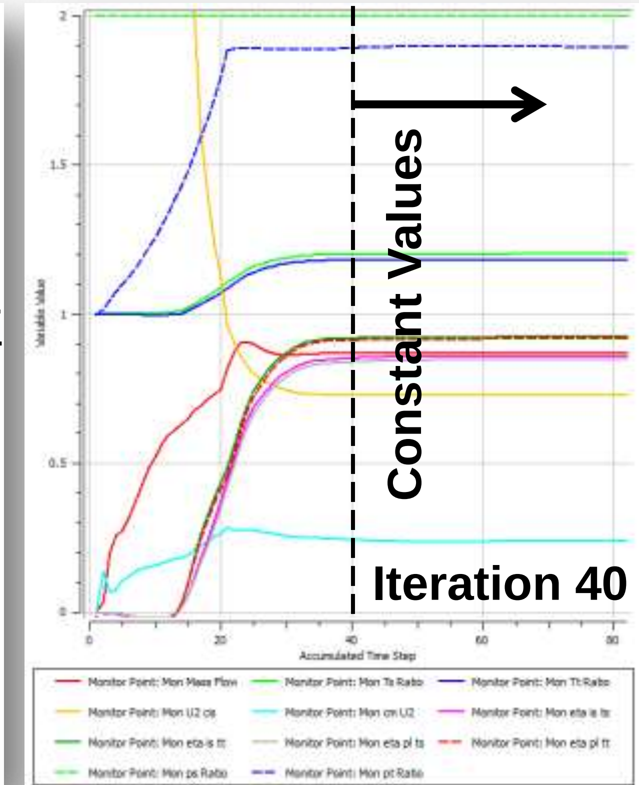


  October 14, 2013

Solver Run







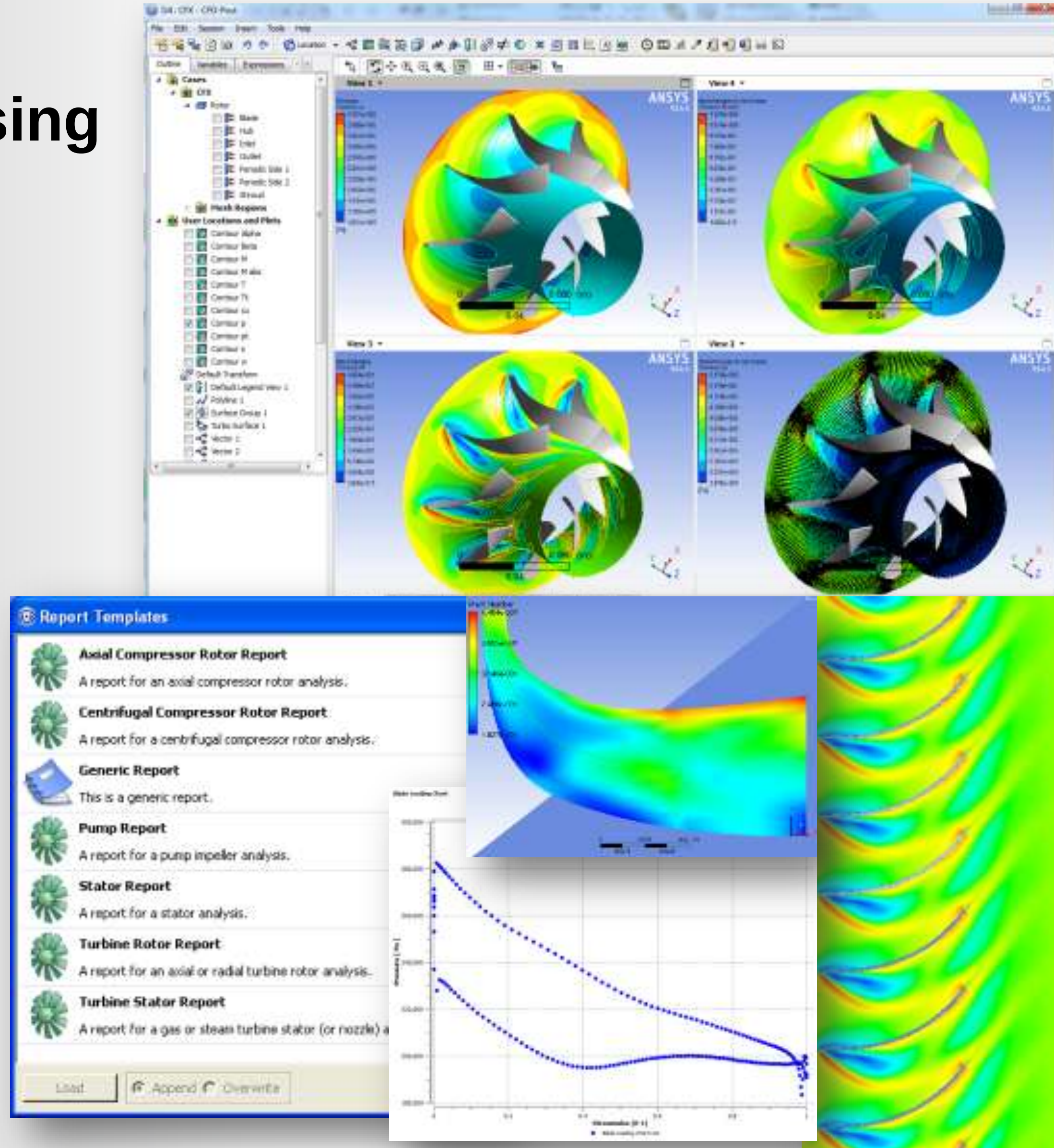
RMS-Residuals
Mass Conservation
Momentum
Energy

Imbalances
Mass Conservation
Momentum
Energy

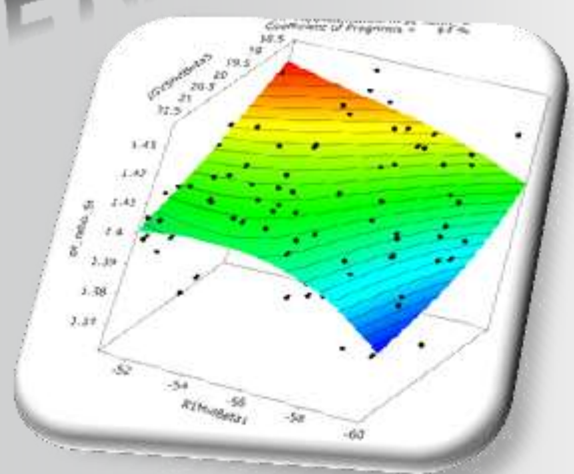
Monitor Points
Efficiency
Variable Ratios
Pressure, Temperature…

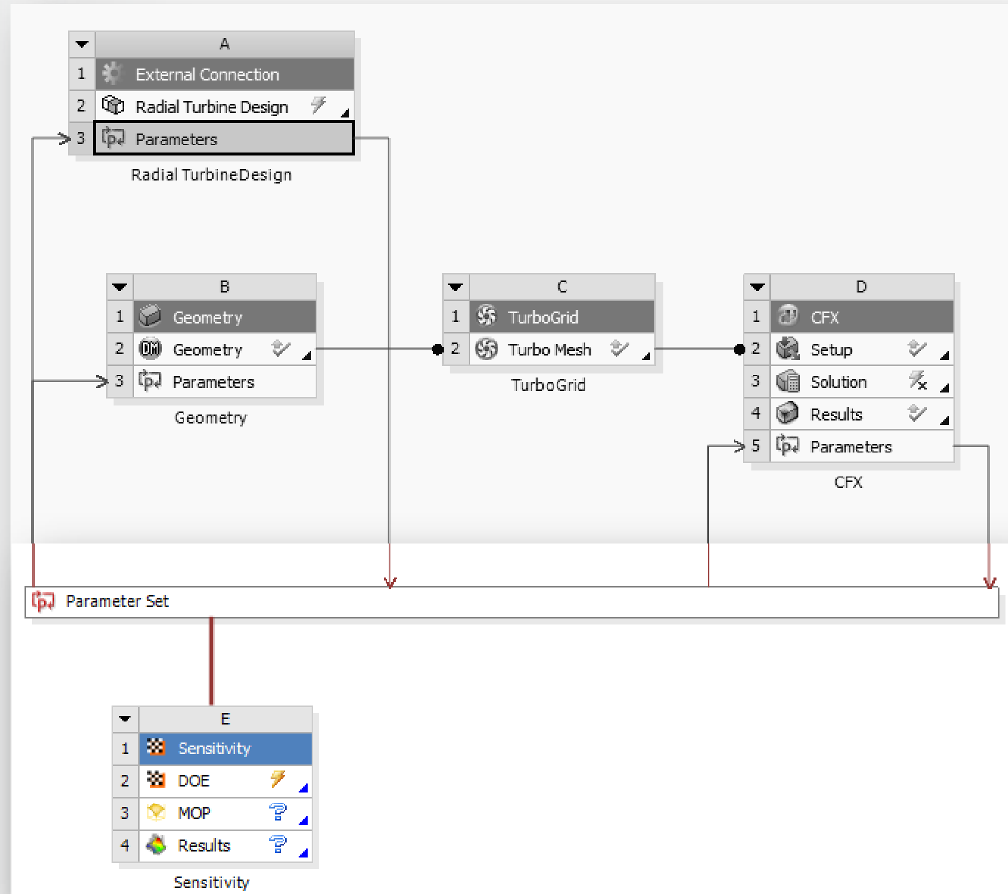
CFX-Post / Turbo-Post

- Turbo post-processing
  - Turbo plots
    - Blade-to-blade
    - Meridional
  - Turbo charts
    - Blade loading
    - Hub to shroud
  - Turbo report templates
    - 1 component → multi-stage

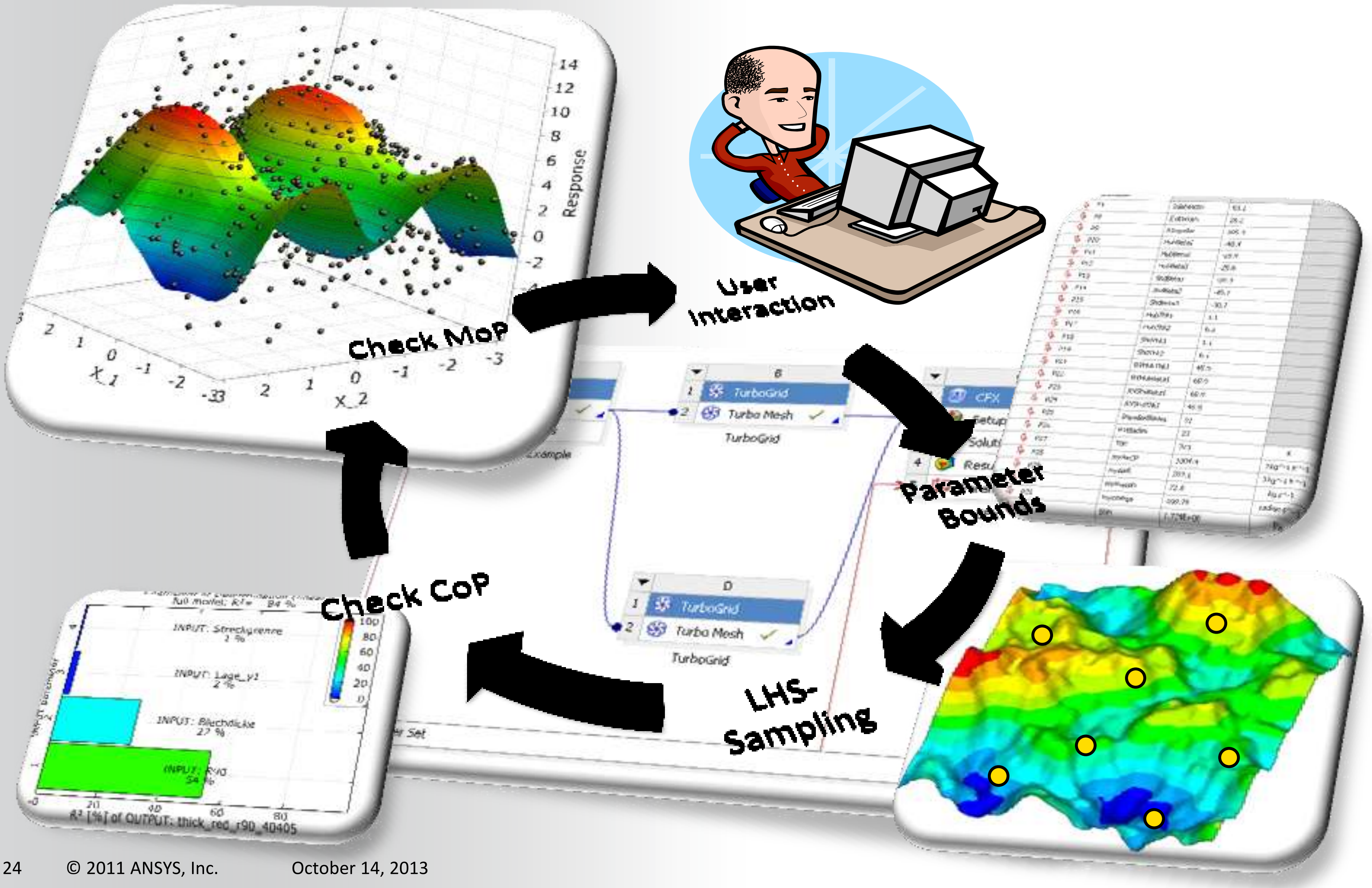


- PRIMARY DESIGN
- GEOMETRY
- CFD-SIMULATION
- META-MODEL

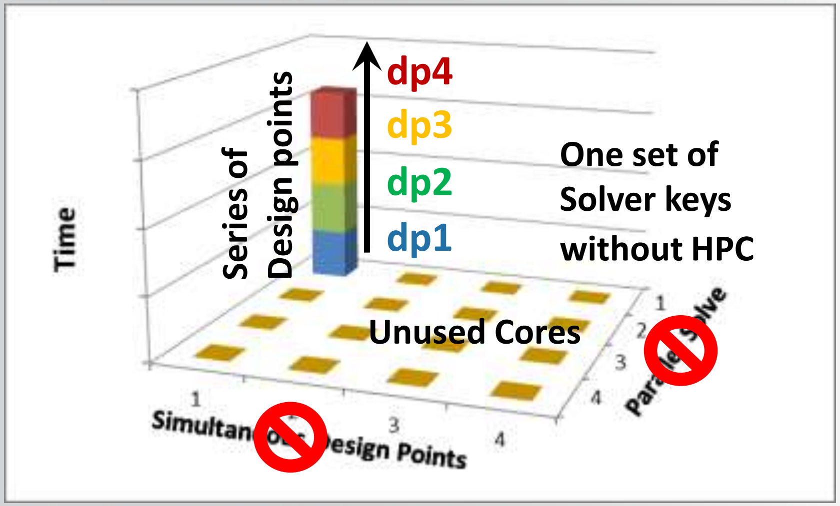




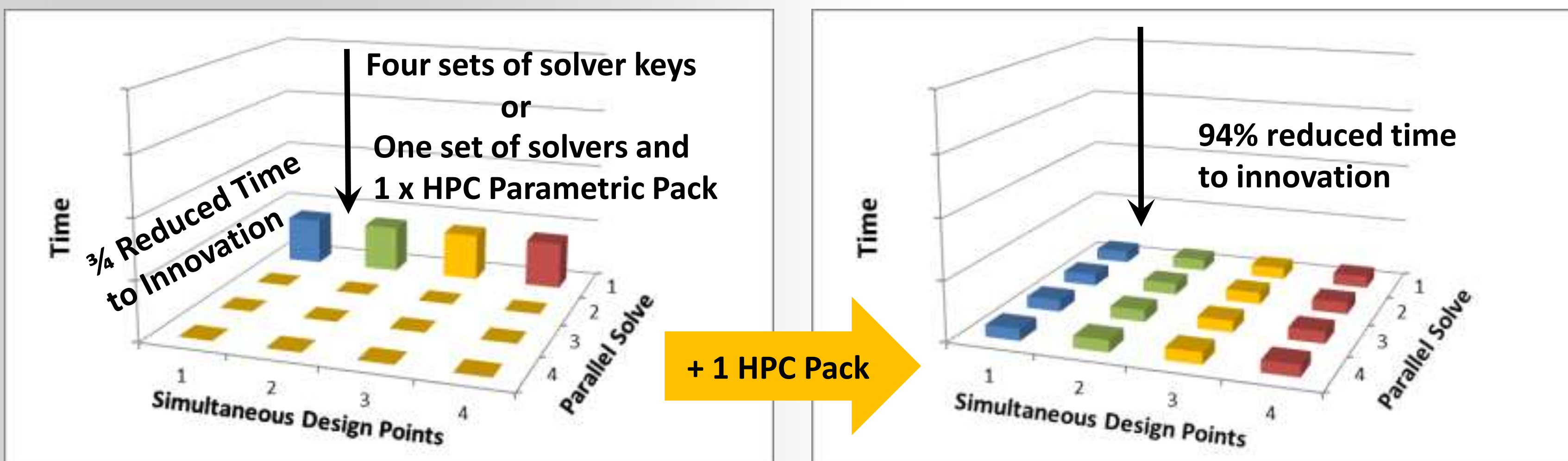
Design of Experiments



Licensing, HPC & Parametric Packs



- A lot of calculations!
- How can these calculations be done in a quick way?



ANSYS

Meta-Model of Optimal Prognosis

Correlation Filter

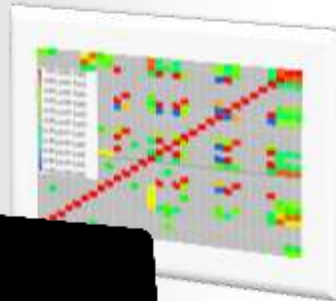
Importance Filter

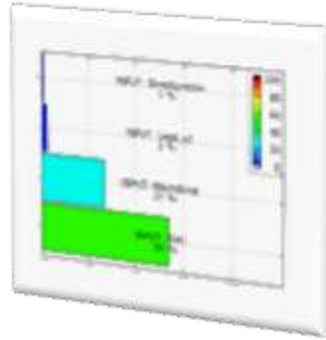
Test-Point & Data Split

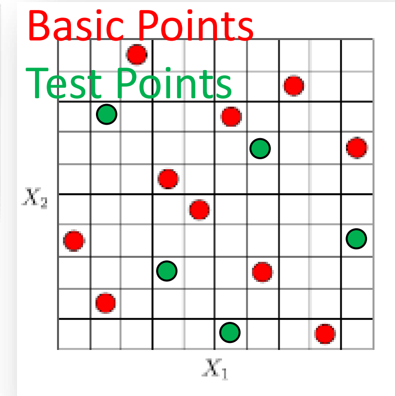
Response Surface

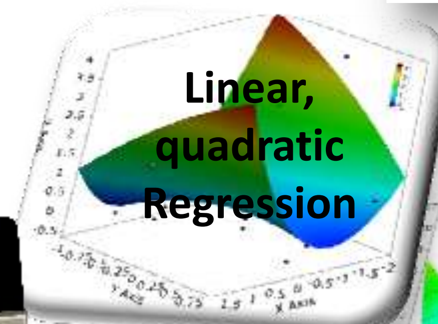
Coefficient of Prognosis

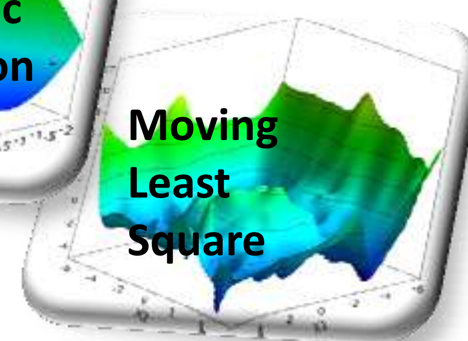
Variation of Filter Limits…







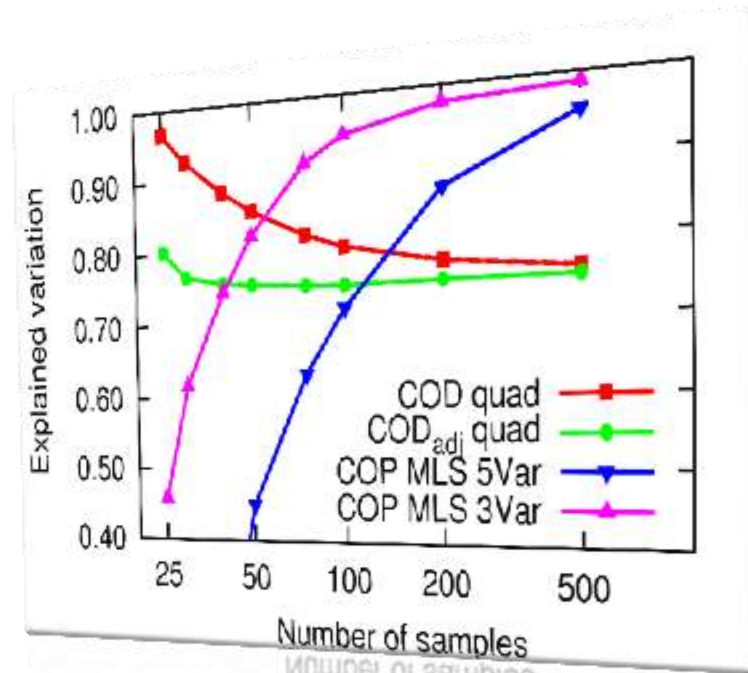


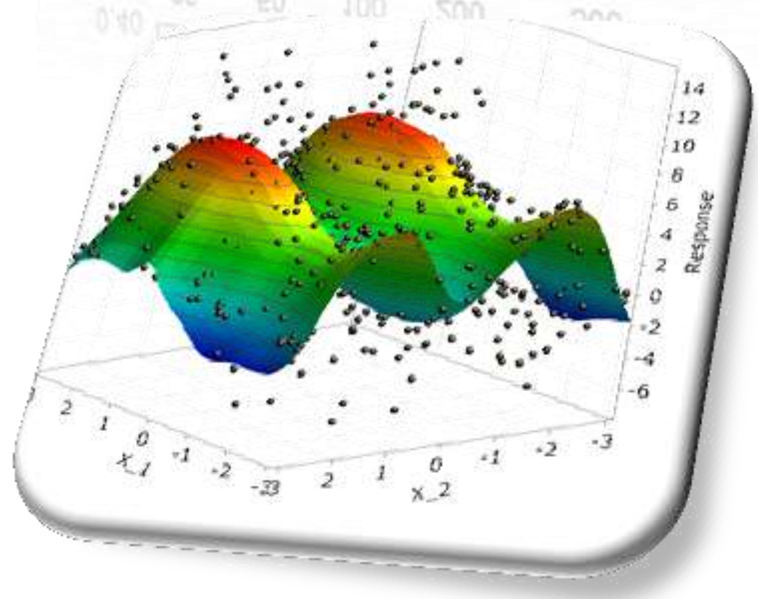


$$CoP = \left(\frac{E\left(Y \cdot \hat{Y}\right)}{\sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2 = \left(\frac{\sum_{k=1}^{N} \left(y^{(k)} - \mu_y\right) \cdot \left(\hat{y}^{(k)} - \mu_{\hat{y}}\right)}{\left(N-1\right) \cdot \sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2$$

Best Practice CoP

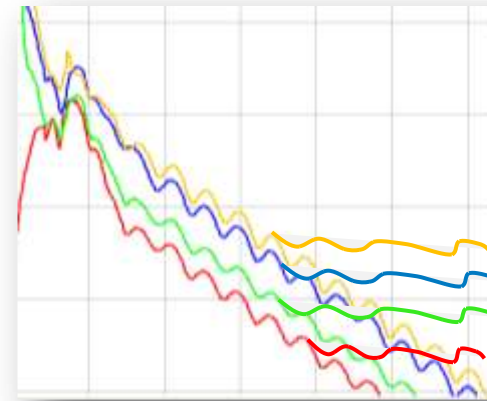
- **CoP is increasing with Number of Samples: 100% or to a Limit → "Noise"**
- **The higher the Dimension of MoP the more Samples are required**
- **The more non-linear MoP is, the more Samples are required**
- **MoP wrt to Lower/Upper Limit of Parameters**

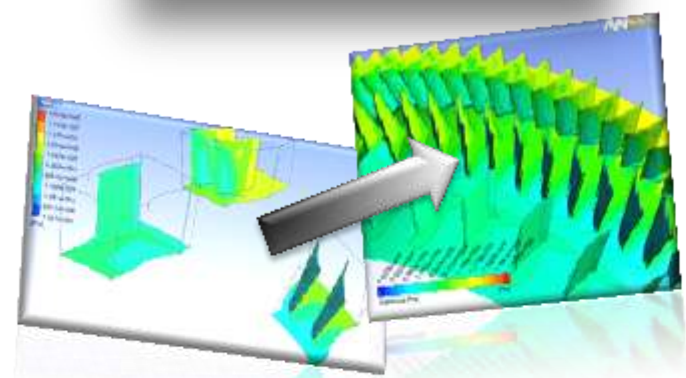


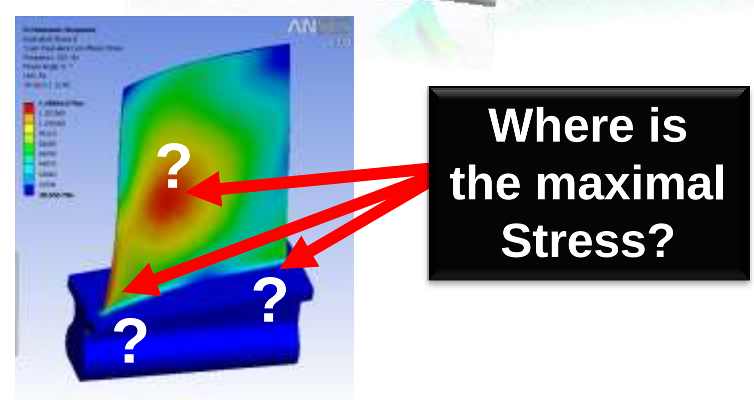


Trouble Shooting for small CoP

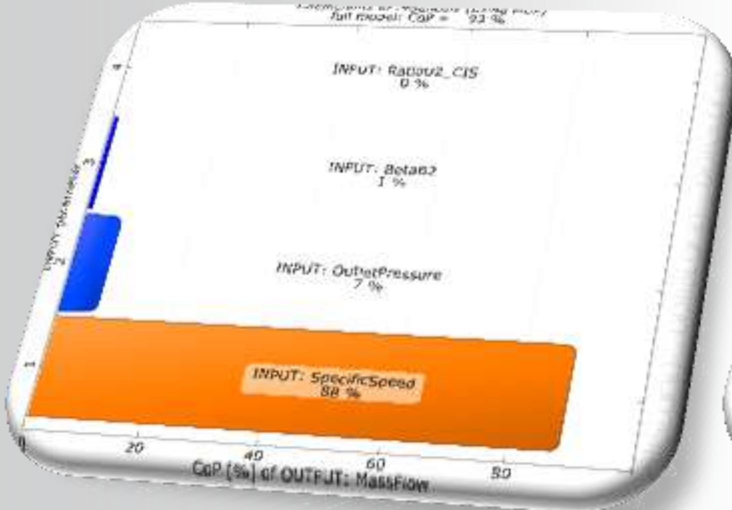
- Number of Evaluated Designs?
  - Check CoP(80)~CoP(150)
- Numerical Error?
  - Best-Practice!
- Model Error?
  - Turbulence Model
  - Steady vs. transient
  - Hot vs. cold Geometry
  - …
- Multiple-Mechanisms
  - Use alternative Output

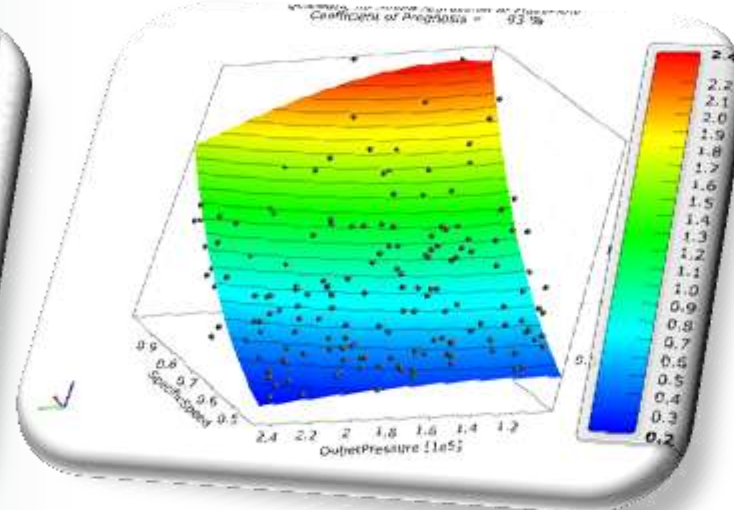




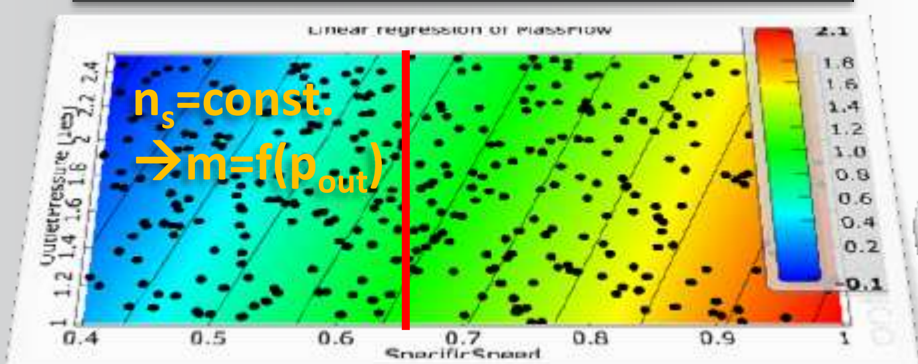


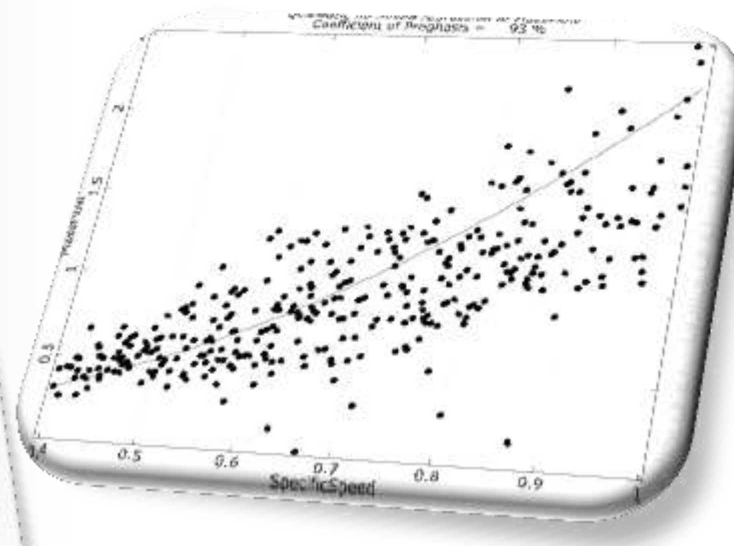
Characteristic Data: Mass Flow Rate





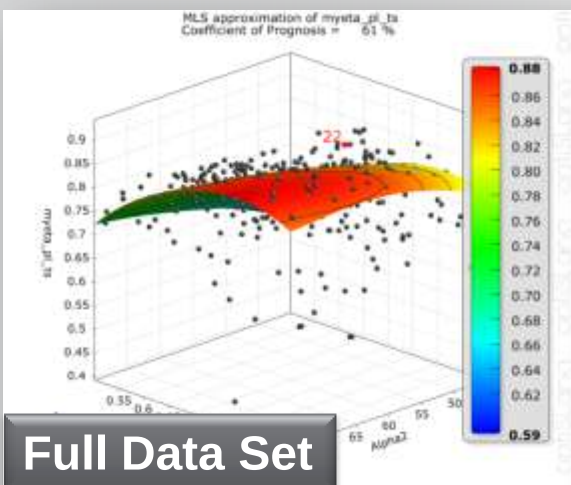
1. High CoP 93%
2. Important Parameters
3. Plausible MoP



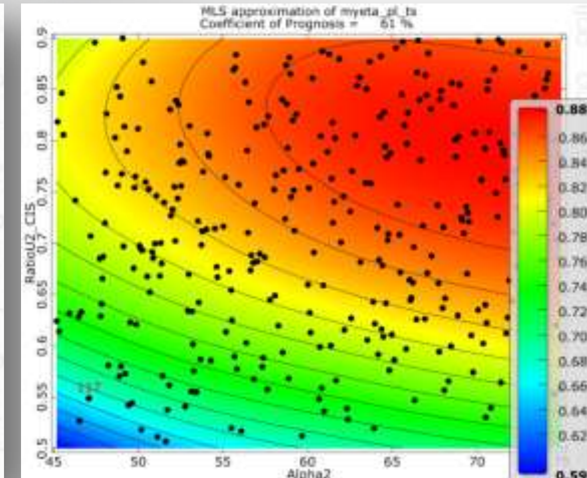


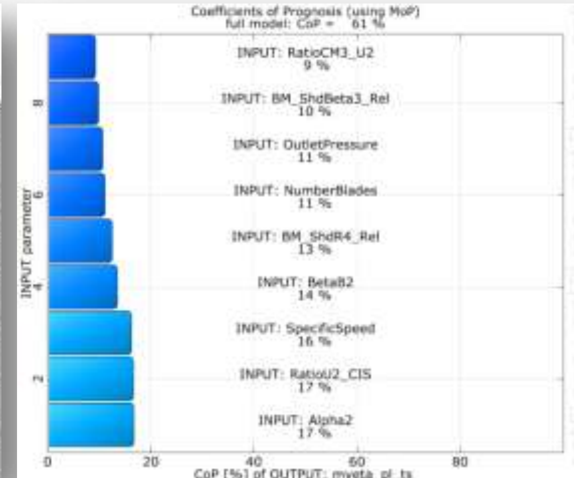
Characteristic Data: Efficiency

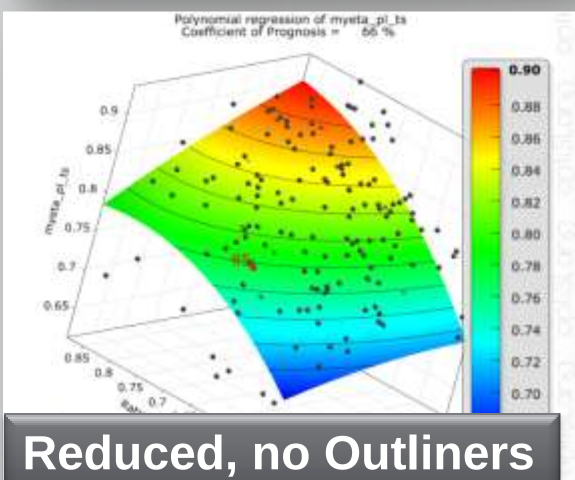
Medium CoP 61% / 66%



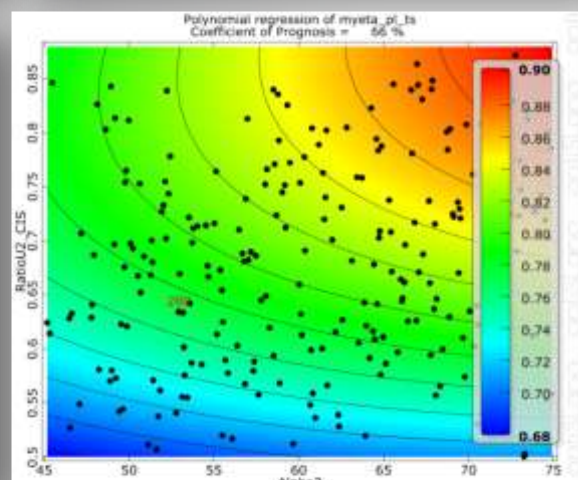
Full Data Set

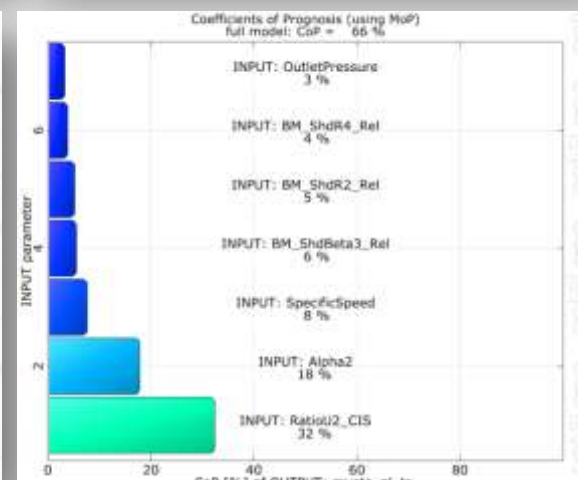






Reduced, no Outliners





Alternative for Efficiency

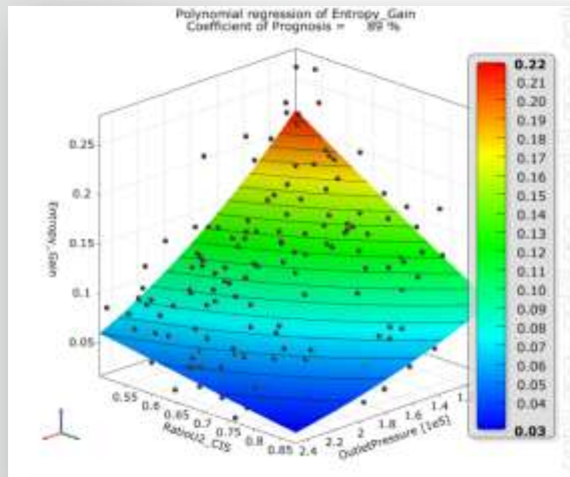
- **Definition of Efficiency:**
  - CoP=66%

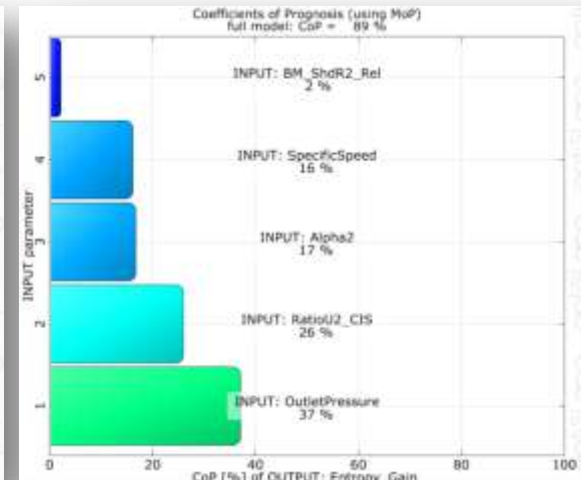
$$\eta_{pl} = \frac{\kappa}{\kappa - 1} \cdot \frac{ln(T_{t4}/T_{t3})}{ln(p_4/p_{t3})}$$

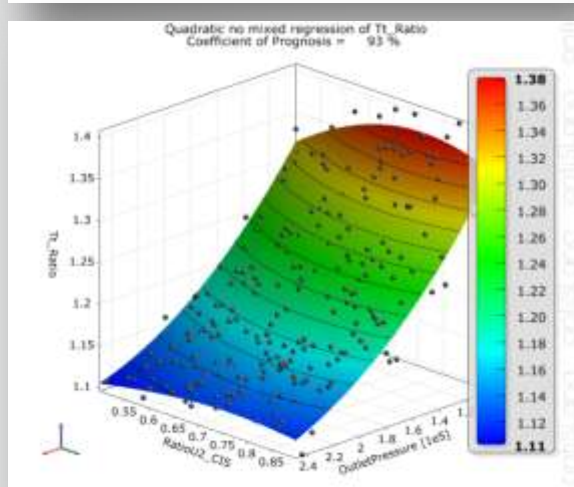
- **Entropy**
  - CoP=89%

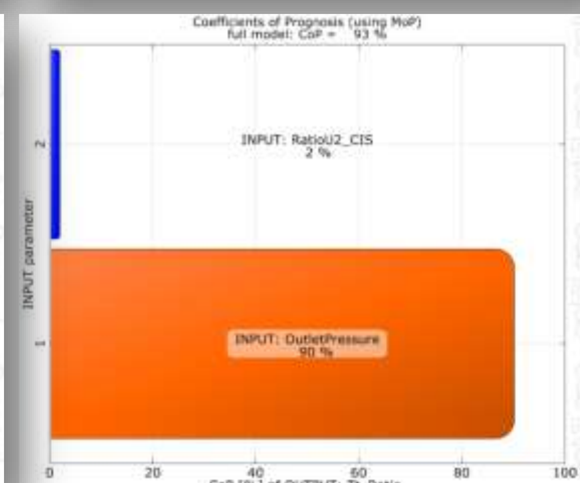
$$\Delta s = c_p \cdot ln\left(\frac{T_4}{T_3}\right) - R \cdot ln\left(\frac{p_4}{p_3}\right)$$

- **Total Temperature**
  - CoP=93%



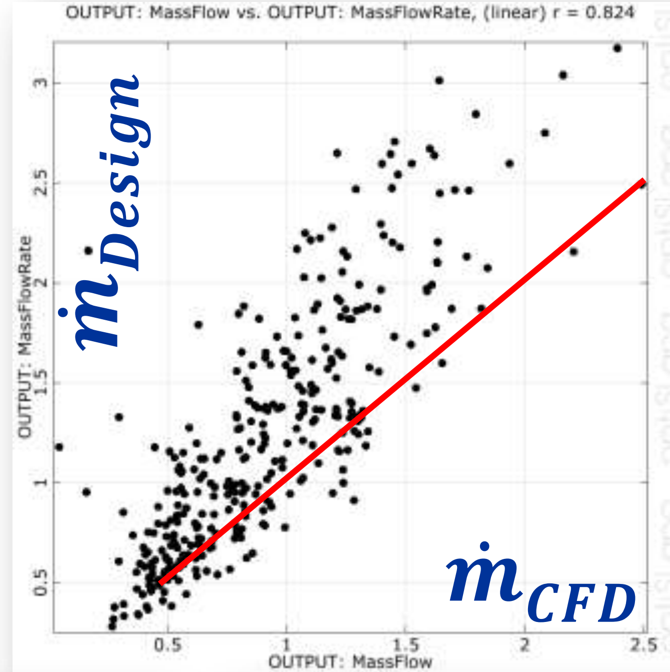


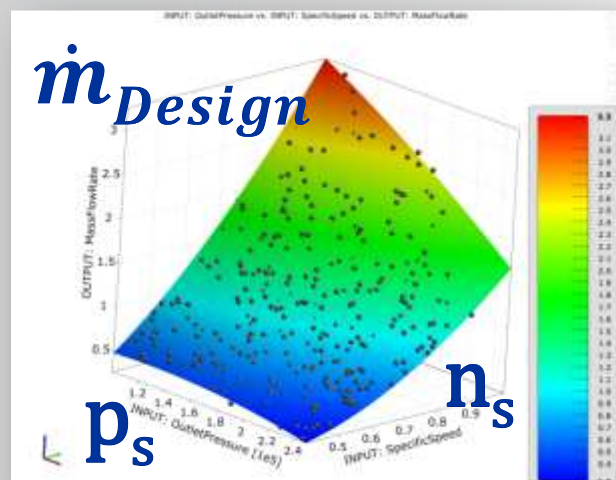


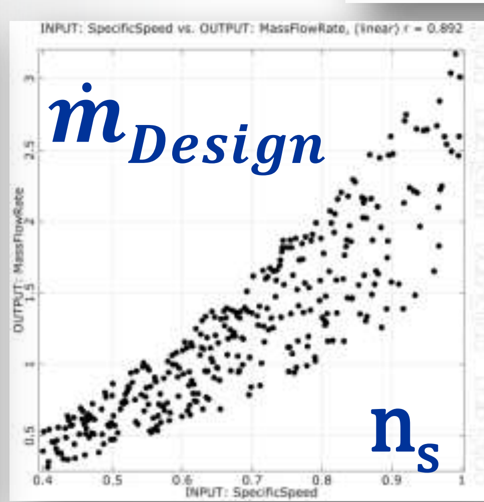


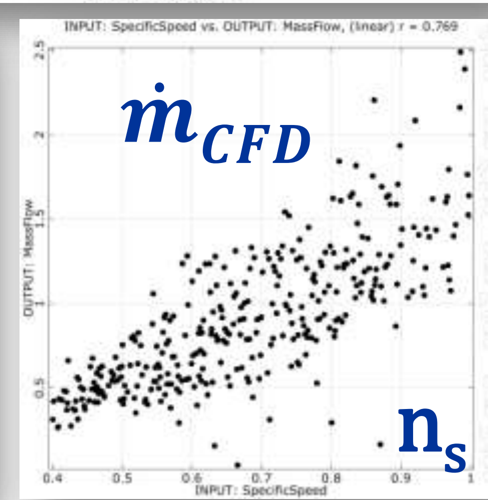
Correlation: Mass Flow Rate

- Real Mass Flow Rate is smaller than predicted due to blockage
- MoP can be used for blockage correlation
- Mass Flow Rate depends on
  - Specific Speed
  - Outlet Pressure
  - Blade Inlet Angle







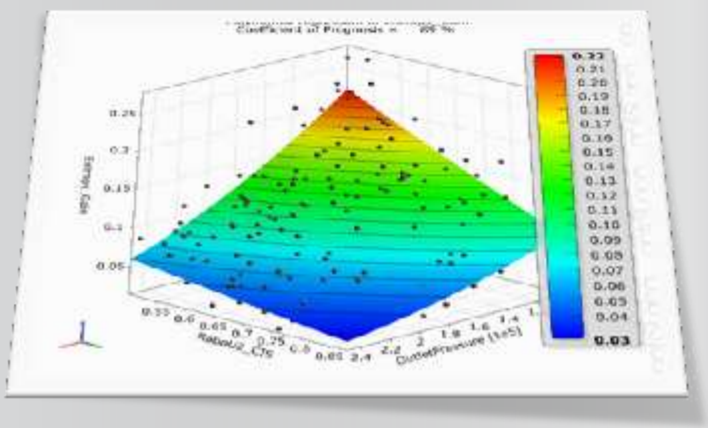


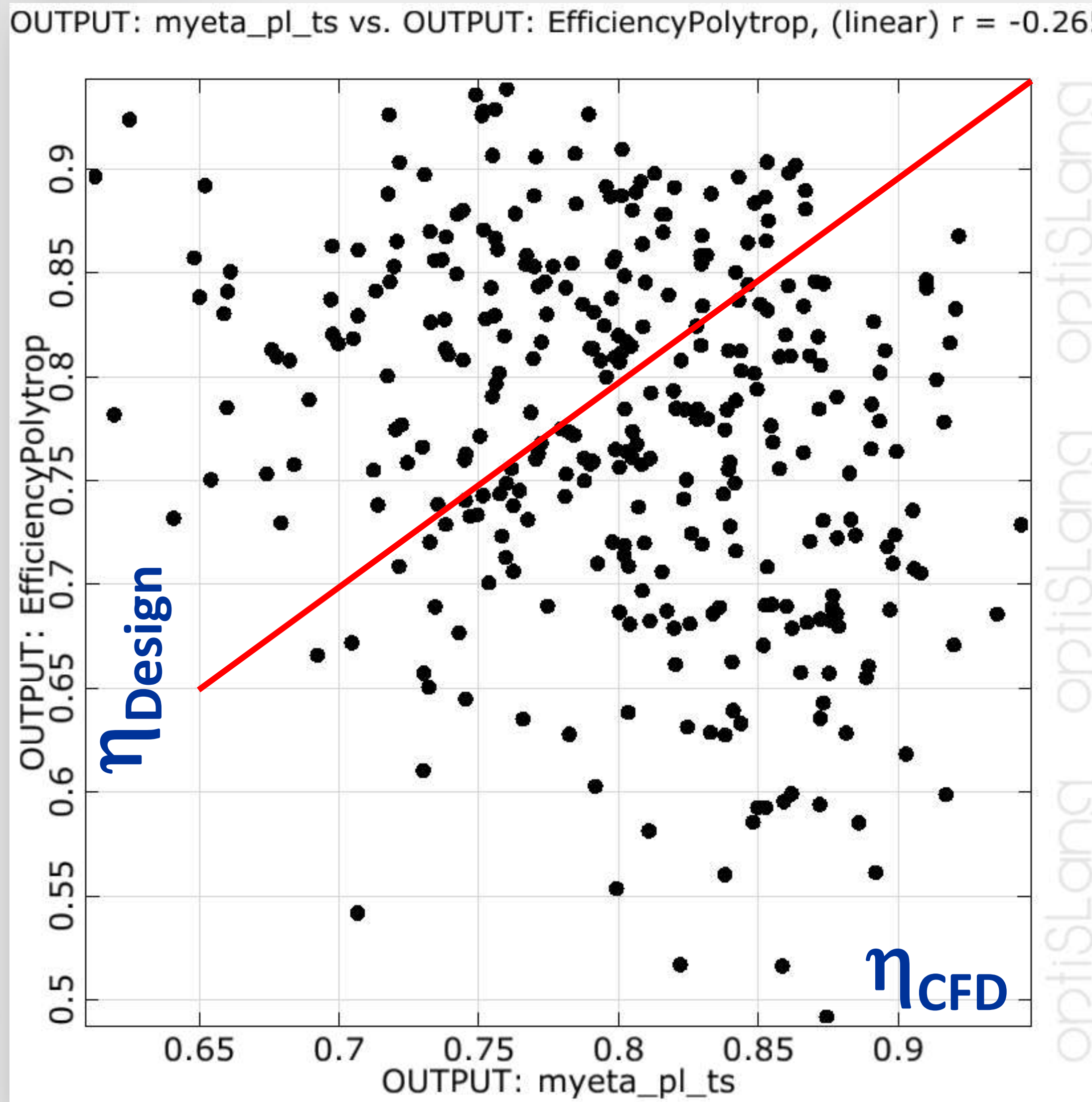
Correlation: Efficiency

Efficiency prediction due to dynamic loss is not sufficient

$$\Delta h_V = 0.5 \cdot \zeta \cdot {c_{m4}}^2$$

MoP for Entropy Gain can be used as prediction for Design Procedure





Summary & Outlook

- **Summary**
  - **Turbine Map as Meta-Model m,η=f(p, Geometry)**
  - **Design Correlations can be derived from Meta-Model**
  - **Primary Design by Meta-Model → turboSLang**

- **Outlook**
  - **Quality might be improved by**
    - Finer Mesh to reduce numerical noise
    - More Design Points in Meta-Model
    - Better Lower/Upper Bounds for Parameter
  - **Turbine Map as Meta-Model m,η=f(p,Ω, Geometry)**
  - **Compressor Map as Meta-Model**