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Parameter based 3D Optimization of the „TU Berlin TurboLab Stator“ with ANSYS optiSLang

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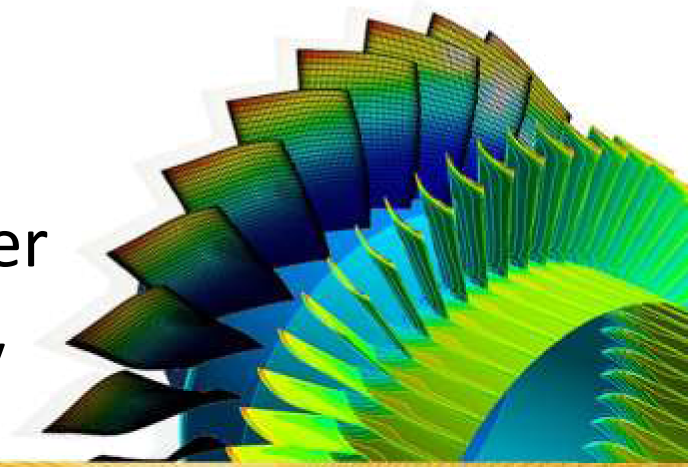
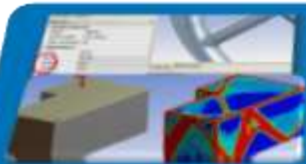


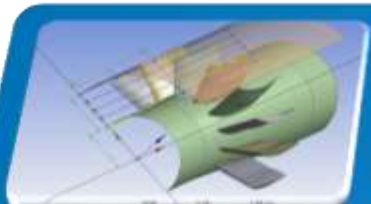
Overview



Adjoint vs. Parameter Based Optimization

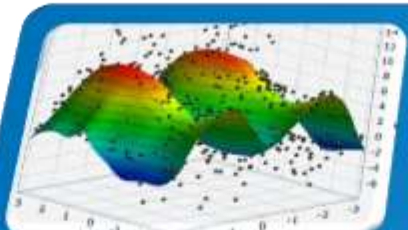
Parameter Based Optimization

- Theory and Strategy



Parametric Simulation Model

- Geometry, Meshing, CFD



TU Berlin TurboLab Stator

- Results

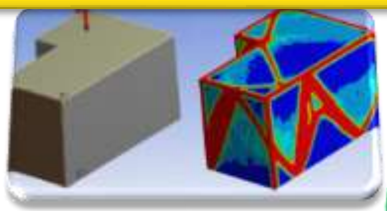
Pro and Cons…

are in opposite

+ / −

Parameter based Optimization

Parameter free Optimization



Parameter based Optimization, pros (+):

- use of established software: CAD, Meshing, Solver…
- automatic add-on tool
- no "non-sense" solution
- optimal Design directly available in CAD

Parameter based Optimization, cons (−):

- „limited" to parameterization
- requires certain amount of solver runs

Parameter free Optimization, pros (+):

- free of limit
- innovative
- Optimization within solver run

Parameter free Optimization, cons (−):

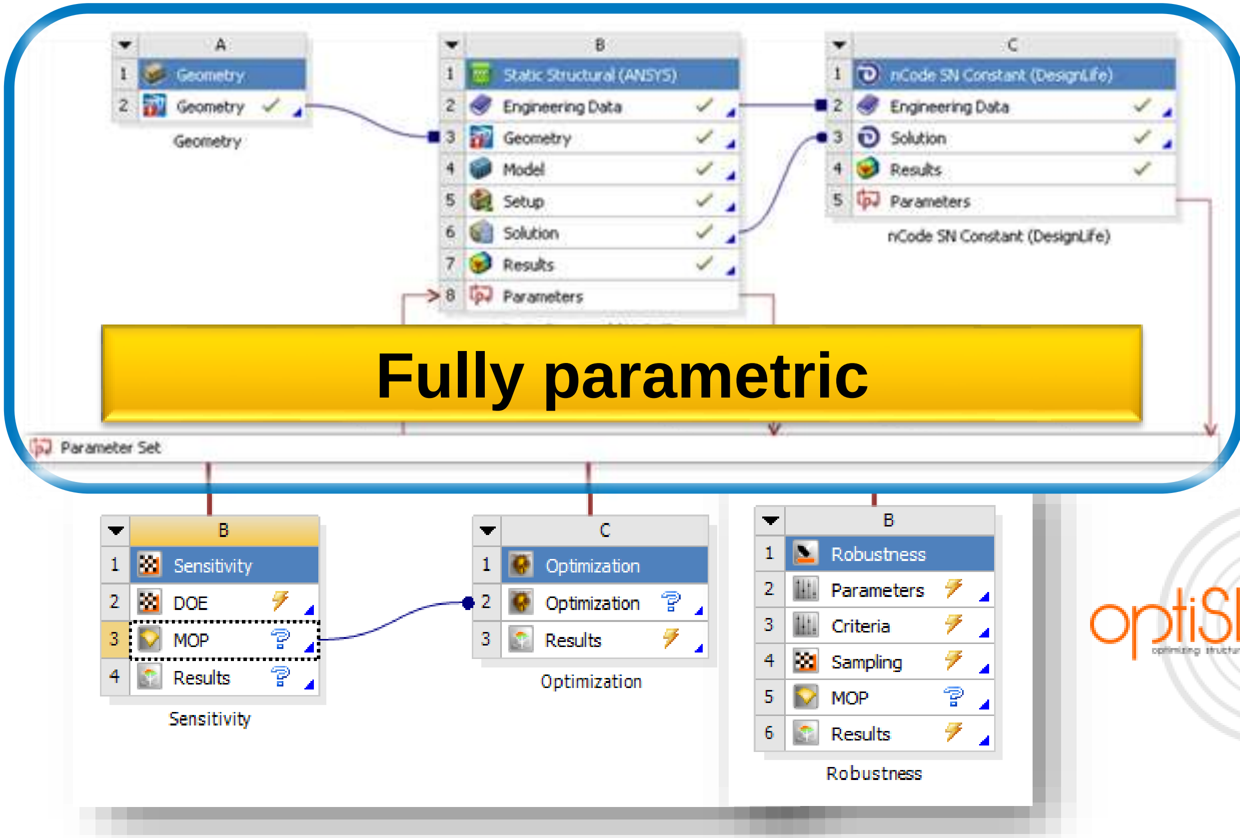
- Optimized designs
  - need to be transferred to CAD
  - Difficult to manufacture
  - are often "non-sense"
- Solver is "different" from established one

Which algorithm is best?
For which application?

Workbench Framework

Optimization inside Workbench

The Workbench Effect – easier to use



Easy parametric set up of complex simulations

optiSLang

easy use of best praxis automated flows inside Workbench

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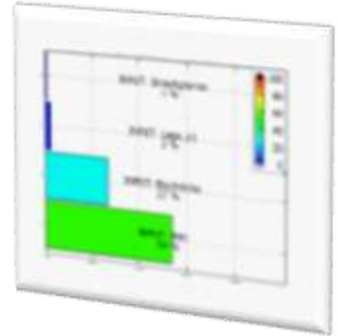
Optimization Strategy

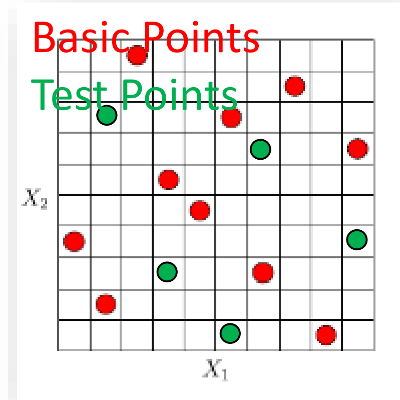
General Procedure:

- Design Optimization
  - Gradient Based
  - Genetic
  - Evolutionary
  -

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

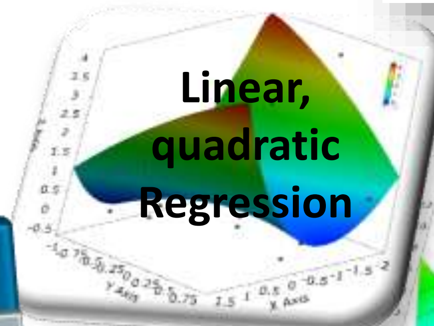
Meta-Model of Optimal Prognosis, MoP

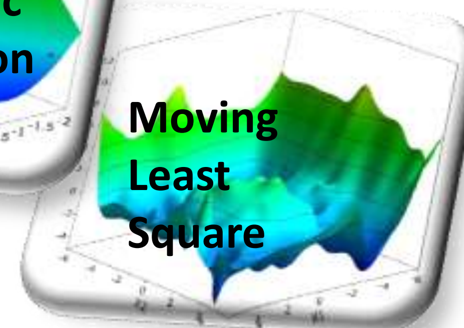




- Significance Filter
- Importance Filter
- Test-Data Point Split
- Response Surface
- Coefficient of Prognosis

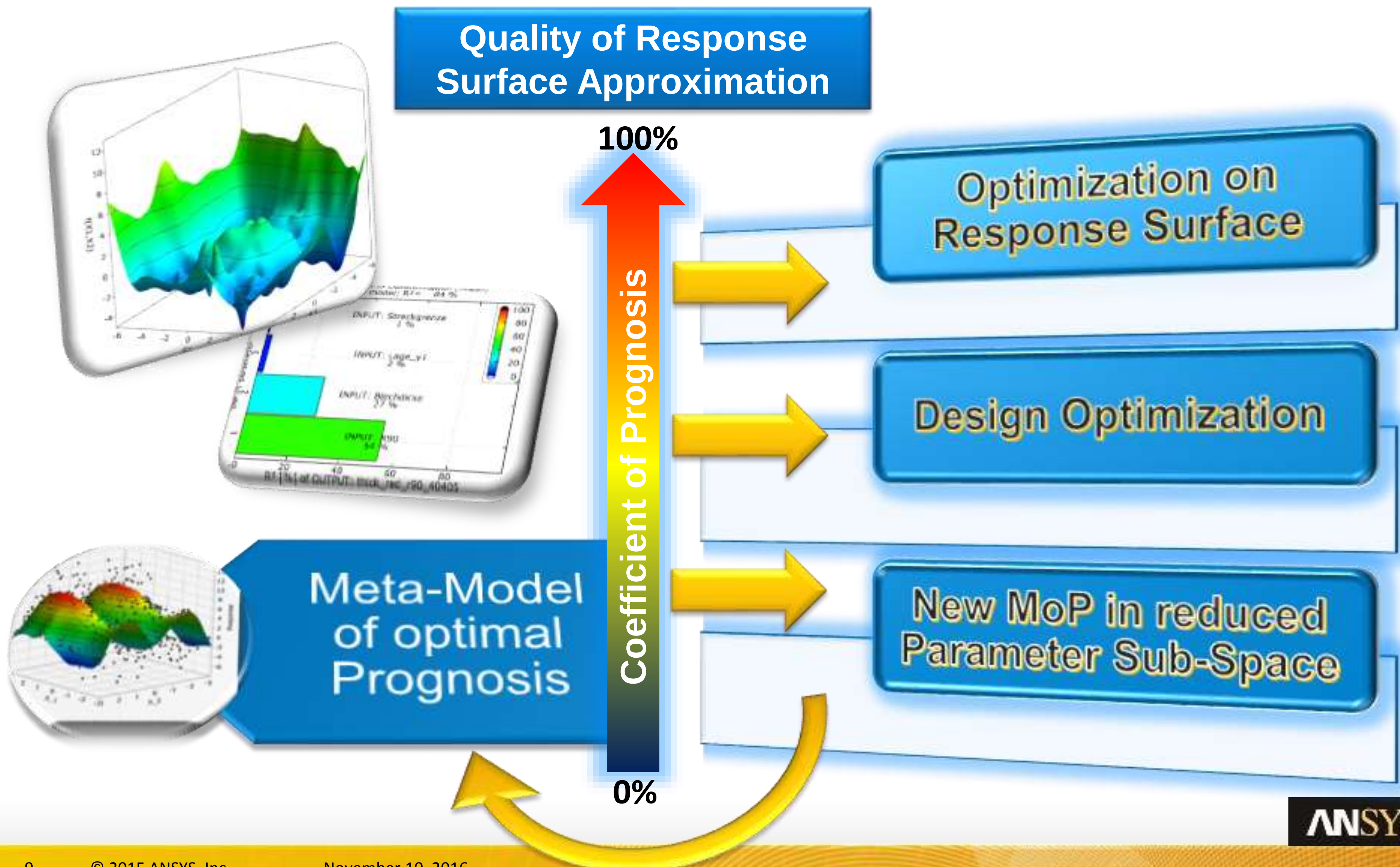
Variation of Filter Limits…



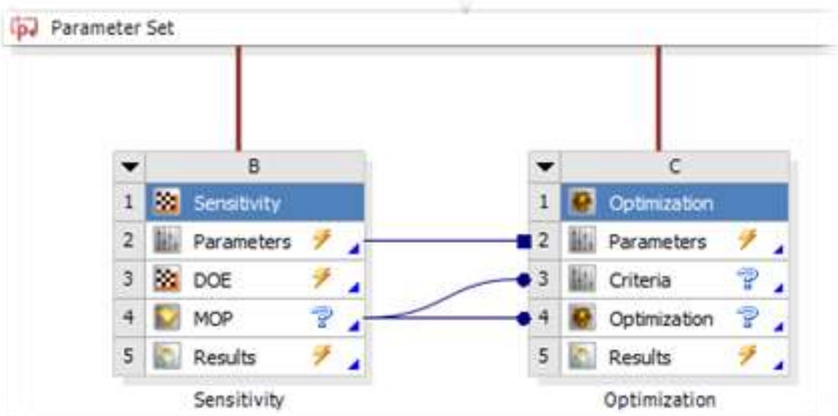


$$CoP = \left(\frac{E\left(Y \cdot \hat{Y}\right)}{\sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2 = \left(\frac{\sum_{k=1}^{N} \left(y^{(k)} - \mu_y\right) \cdot \left(\hat{y}^{(k)} - \mu_{\hat{y}}\right)}{\left(N-1\right) \cdot \sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2$$

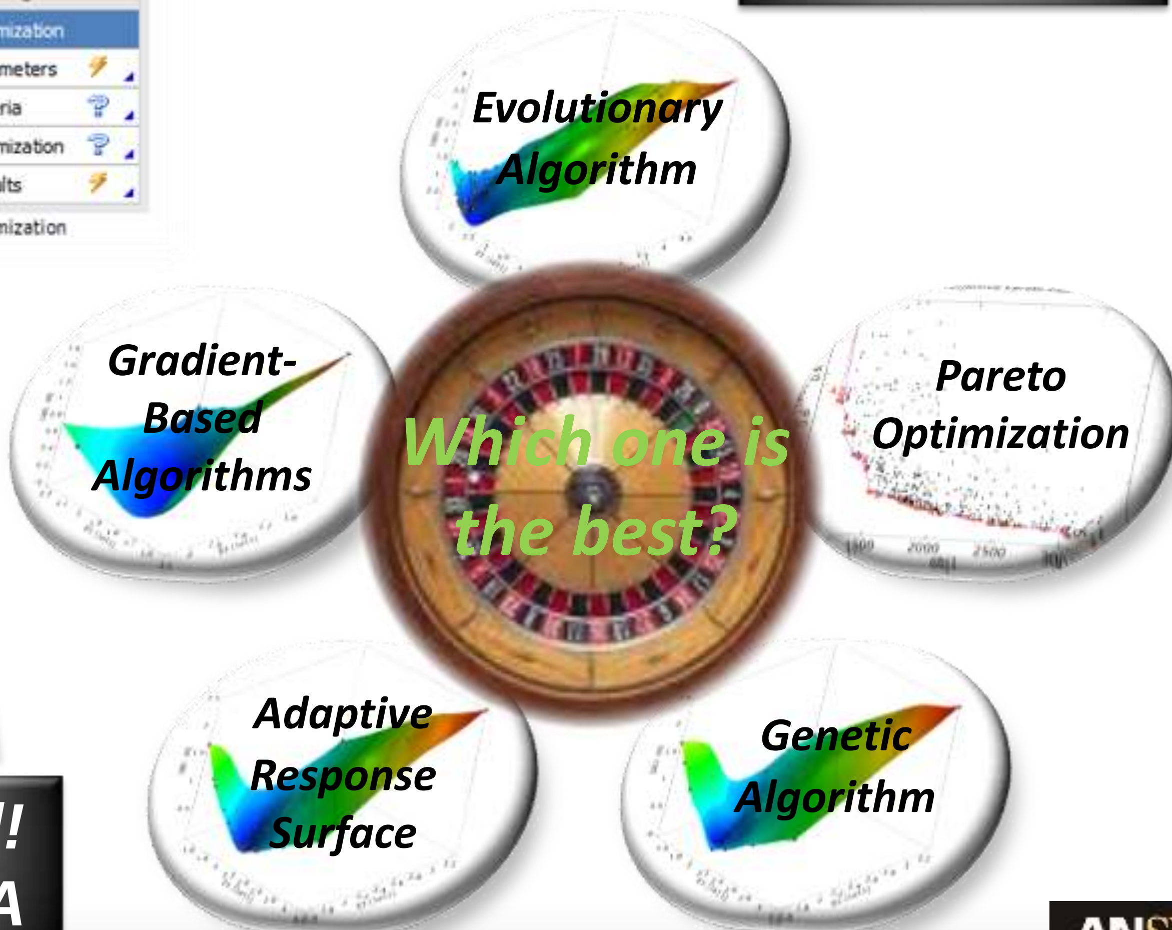
Optimization Strategy, wrt to CoP



Design Optimization



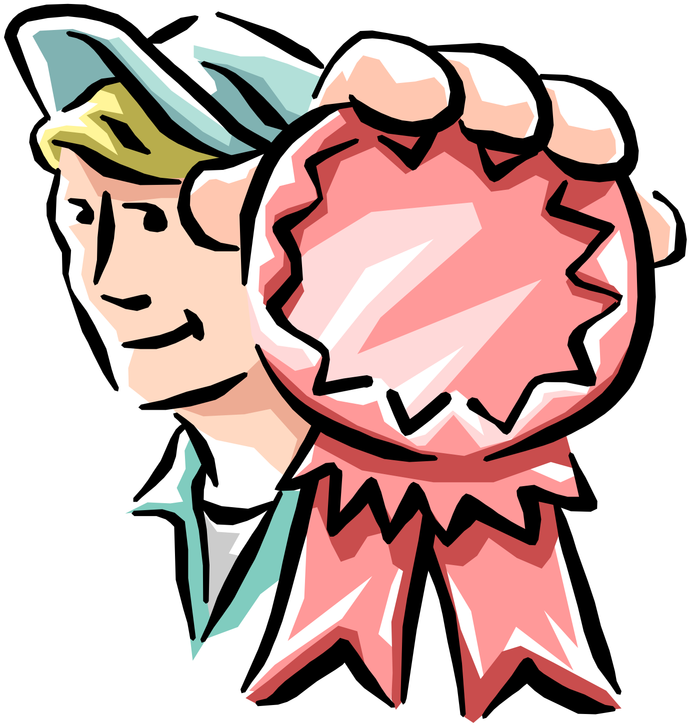
Optimization Algorithms:



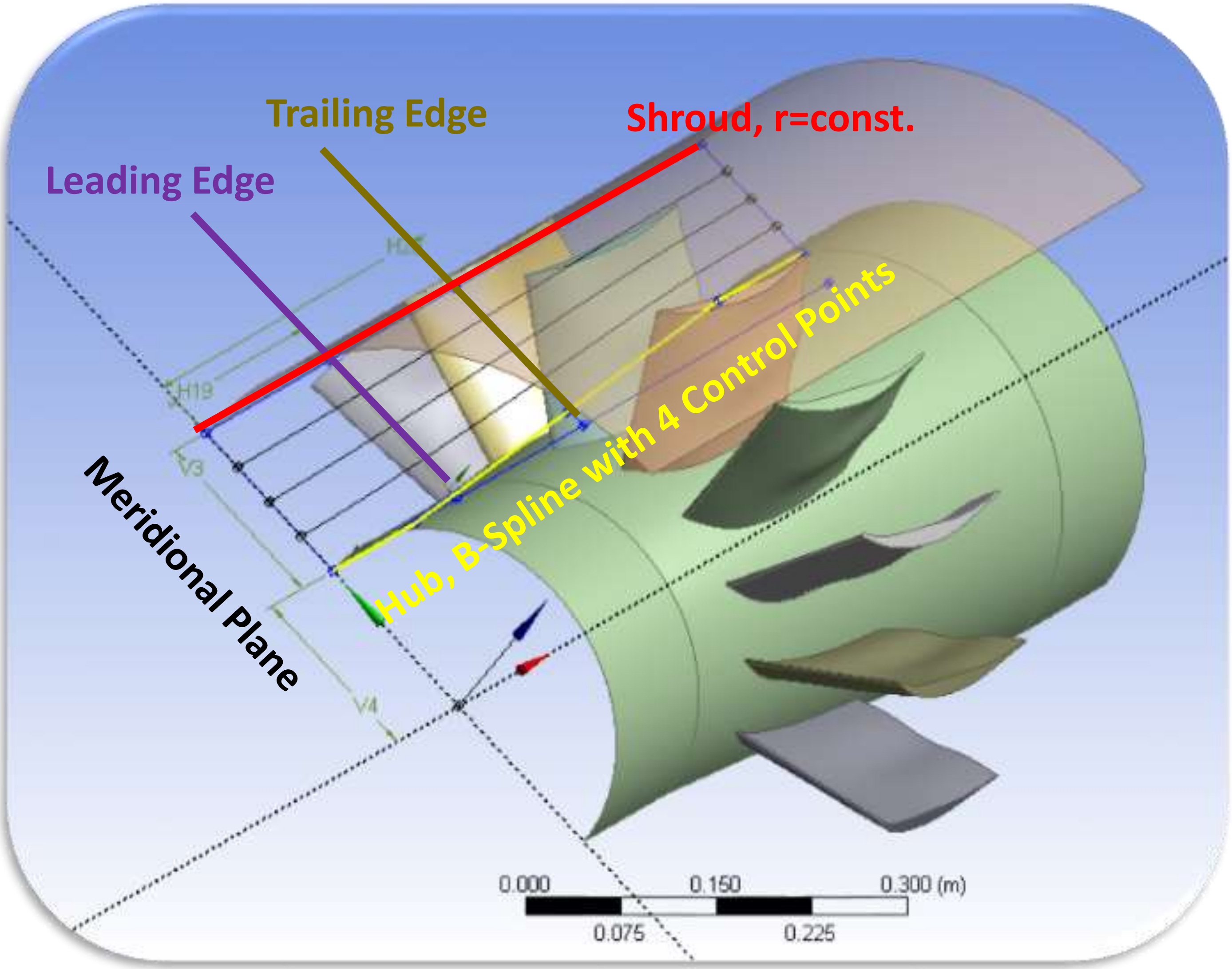
Strategy is required! and derived from SA

Meta-Model of Optimal Prognosis, Best-Practice

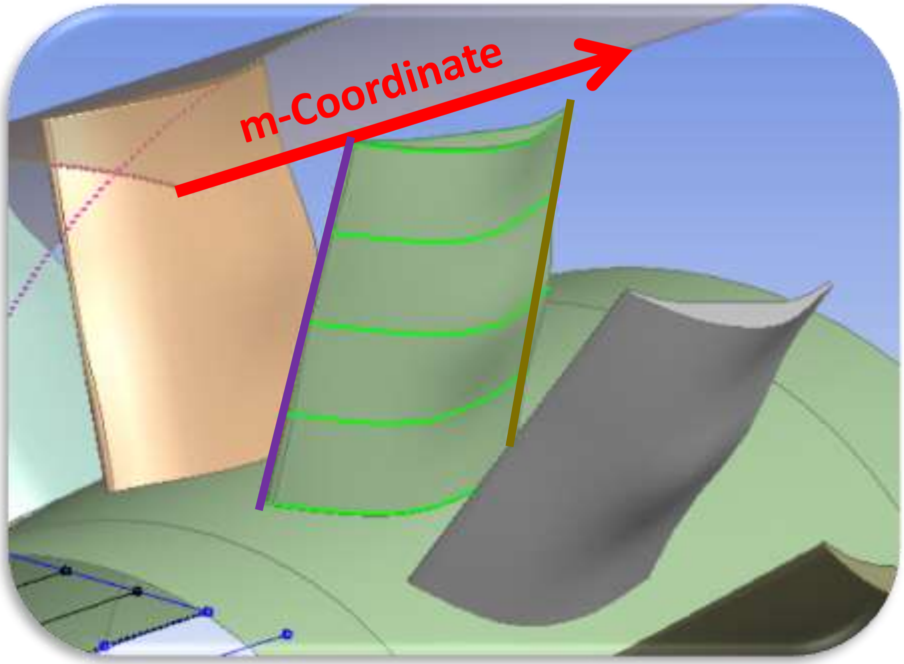
- Number of Evaluated Designs?
  - Required Designs=f(#Important Variables, Non-linearity)
  - Check CoP for different number of Designs
- Numerical Error?
  - Best-Practice CFD!
- Model Error?
- Options:
  - Design Optimization
  - Meta-Model in Subspace

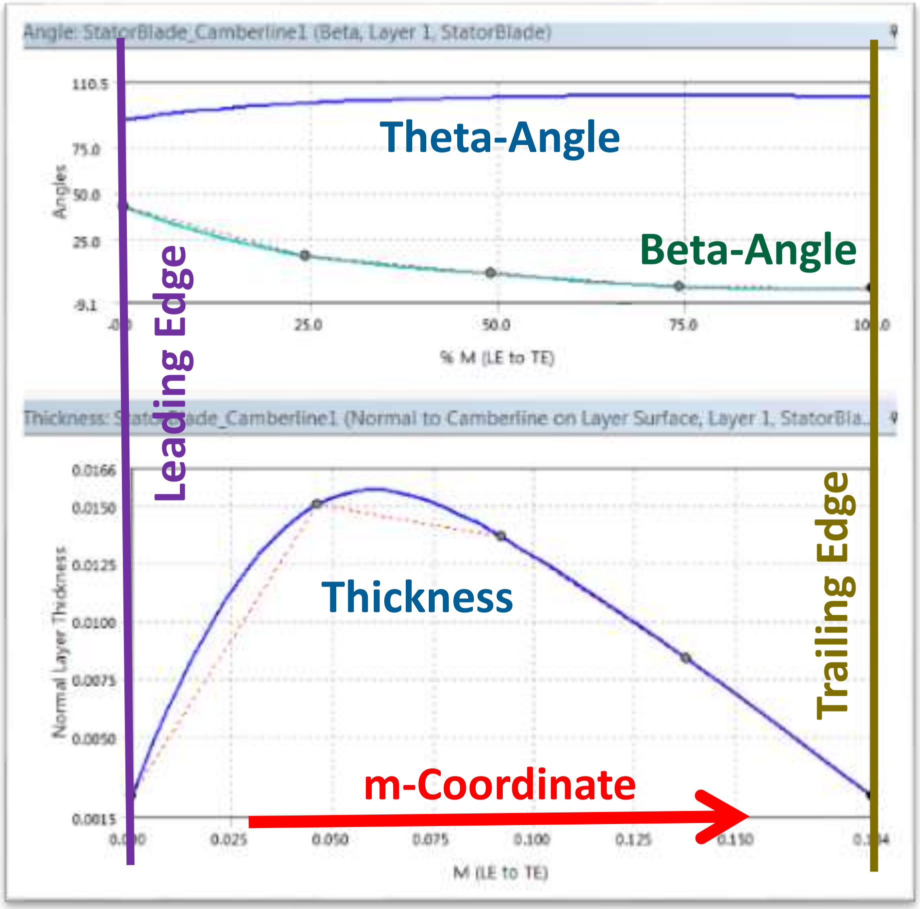


Parametric Geometry – Meridional Design



Parametric Geometry – Blade Design

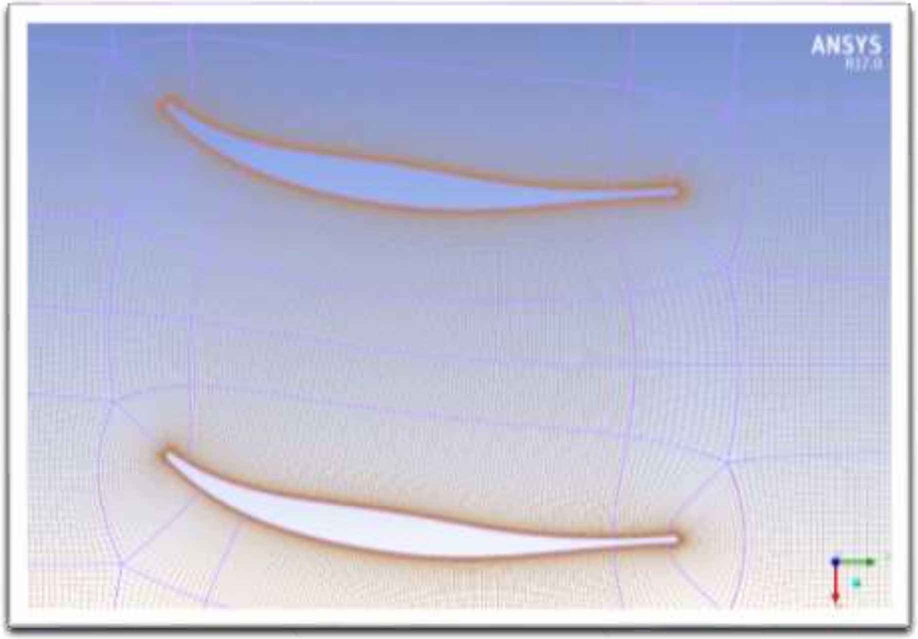


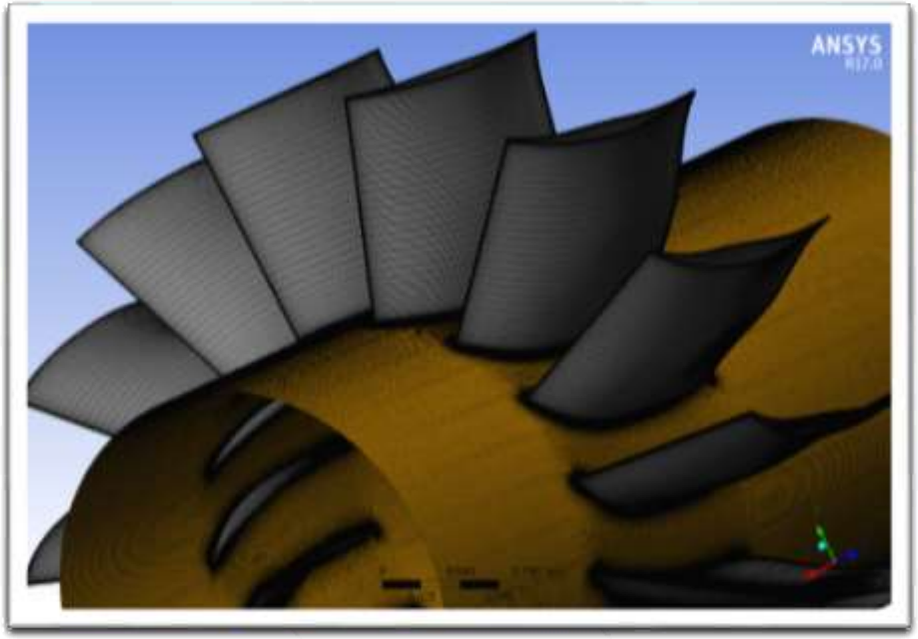


Blade Design on 5 Layers:

- **Blade (Beta) Angles: Bezier-Curve, 5 Control Points**
- **Thickness Distribution: Bezier-Curve, 5 Control Points**

Meshing



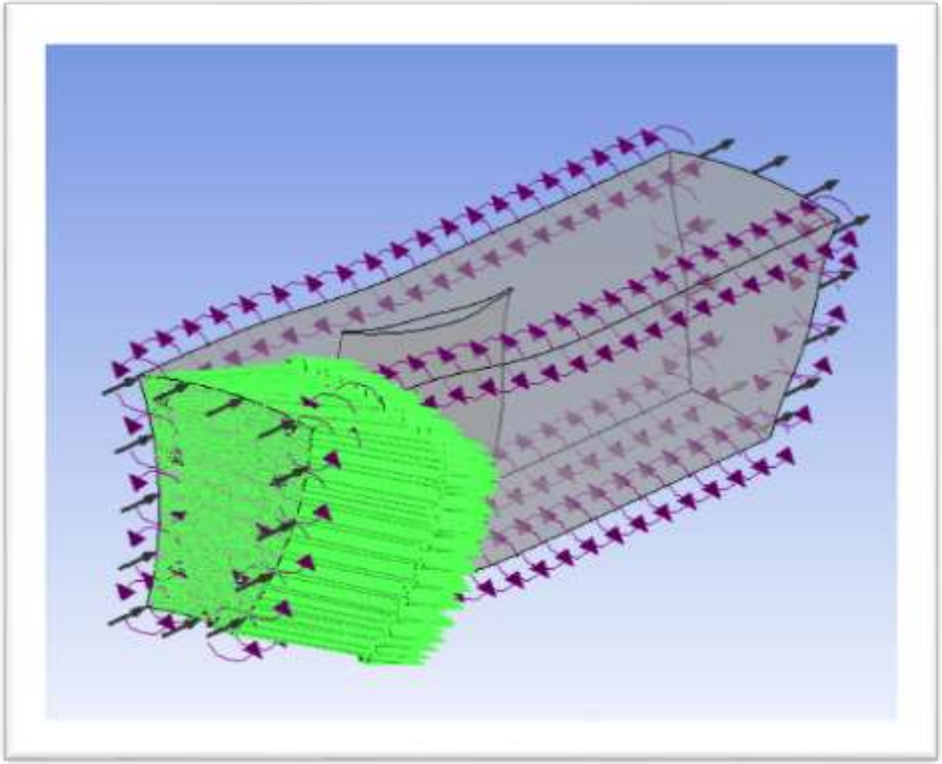


Scalable Block Structured Mesh, automatically smoothed

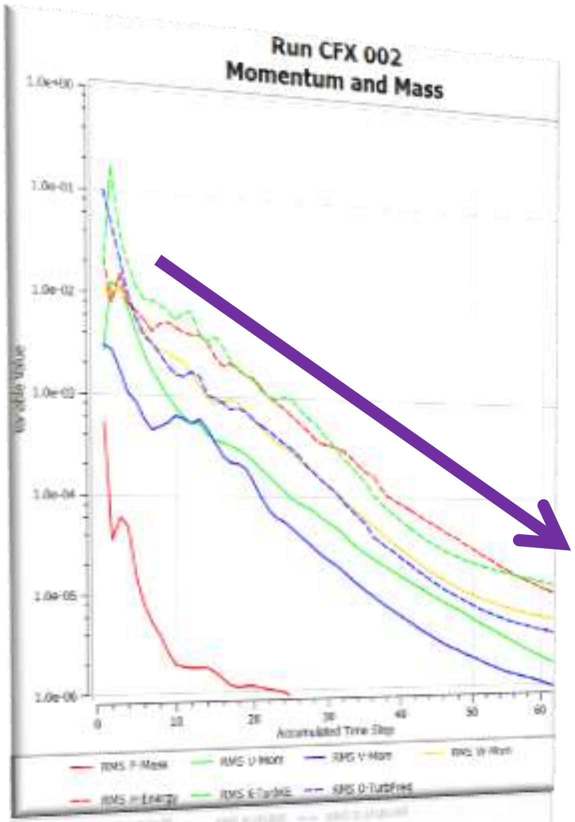
#Control Volumes	Min Angle [°]	Volume Ratio [-]
500000	46.4	2.90
1000000	46.0	2.37
2000000	45.3	2.13
4000000	45.8	1.92

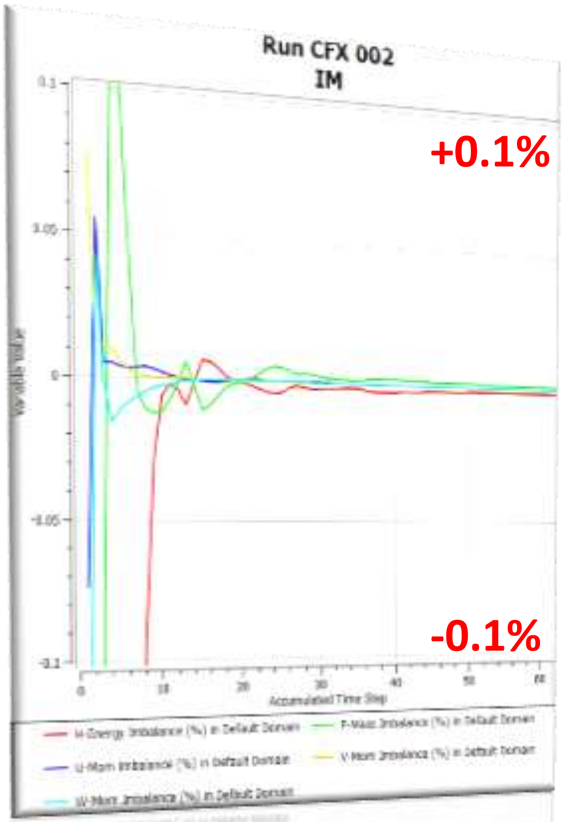
CFD Set-Up

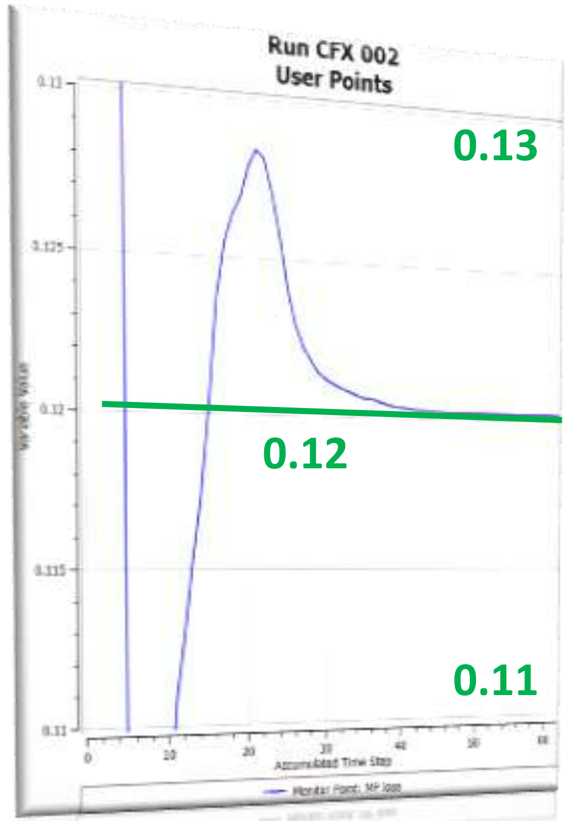
- Model: 1 Segment with periodic boundary conditions
- Material: Air Ideal Gas
  - R = 287 [J/kg/K]
  - c_p = 1004 [J/kg/K]
- Equation System:
  - Mass
  - Momentum
  - Total Energy (+viscous heating)
  - SST Turbulence Model
- Inlet:
  - Total Pressure=102713.0[Pa]
  - Total Temperature=294.314 [K]
  - Flow Angle (wrt axis)=42°
- Outlet:
  - Mass Flow Rate (360°)=9.0 [kg/s]



CFD, Convergence Study





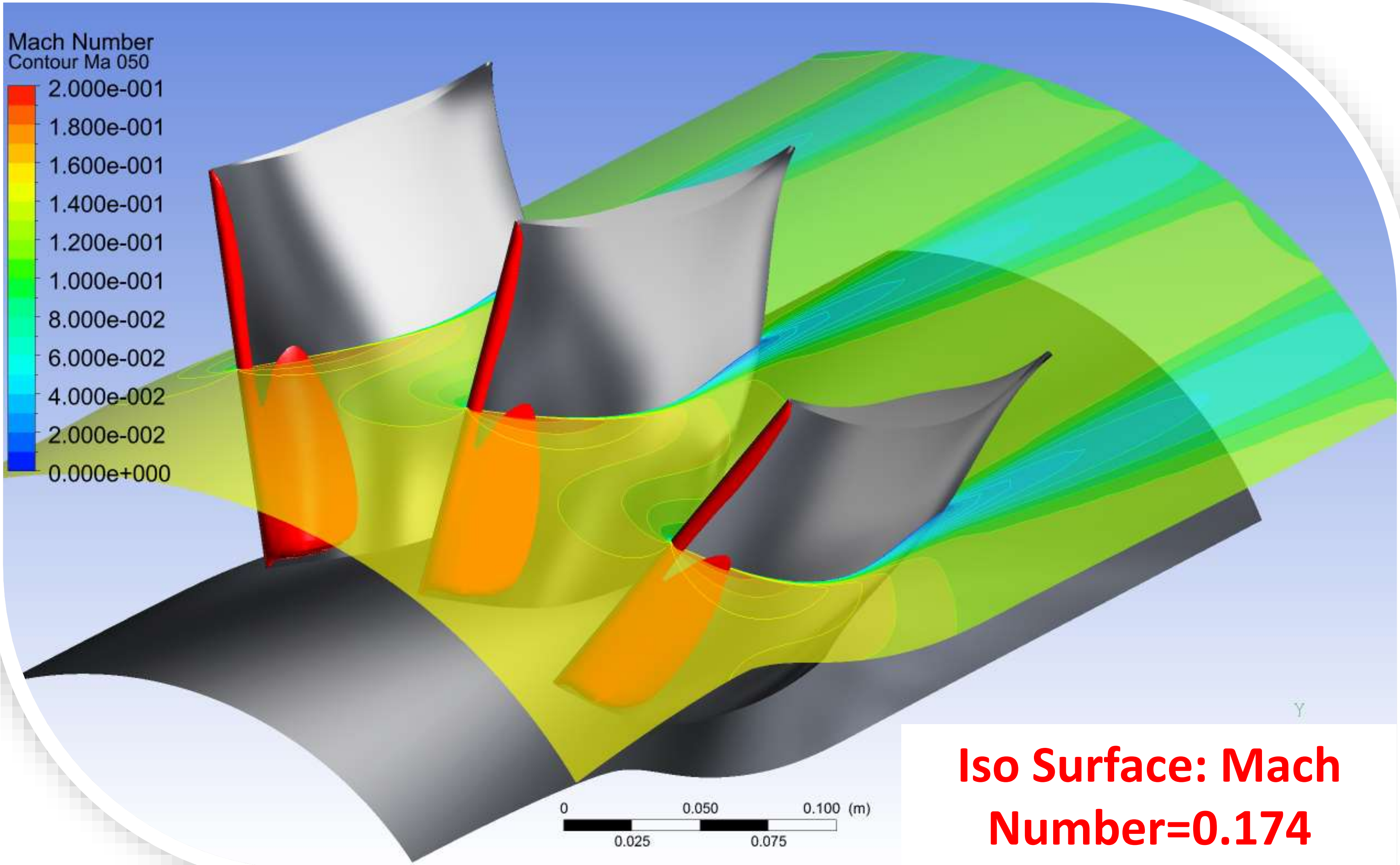


Monotonic convergence of all residuals

Abs of all imbalances lower than 0.01%

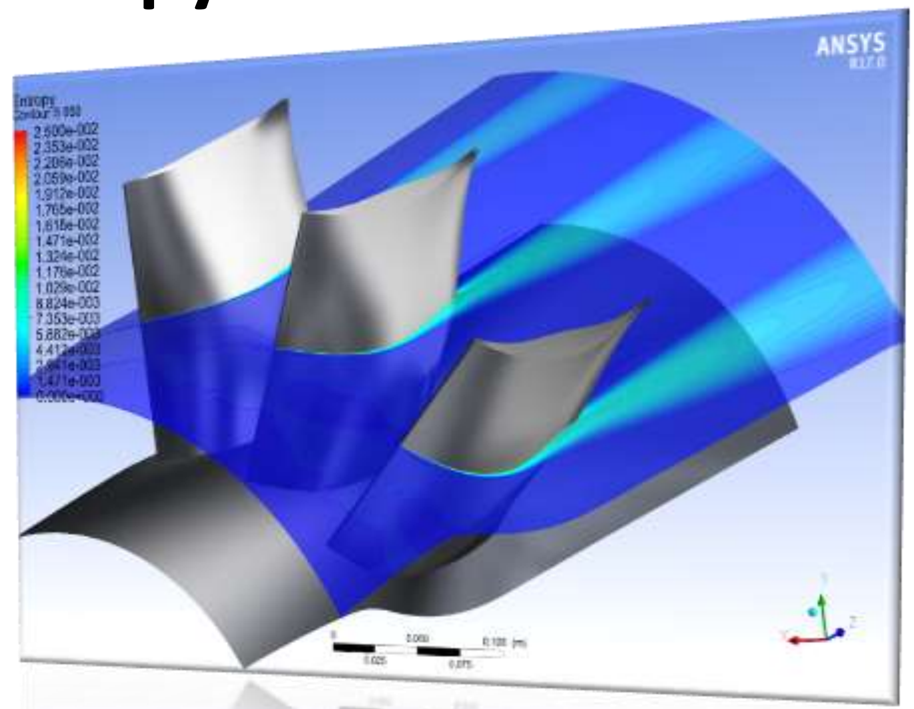
Monitor value stationary

CFD Result - Mach Number



Iso Surface: Mach Number=0.174

CFD Result – Losses and Entropy



<u>Incompressible Loss Definition:</u>

pt in = massFlowAve(Total Pressure)@Inlet
pt out = massFlowAve(Total Pressure)@Outlet
ps in = massFlowAve(Pressure)@Inlet
Loss = (pt in – pt out)/(pt in – ps in)

<u>Thermodynamic Loss Definition:</u>

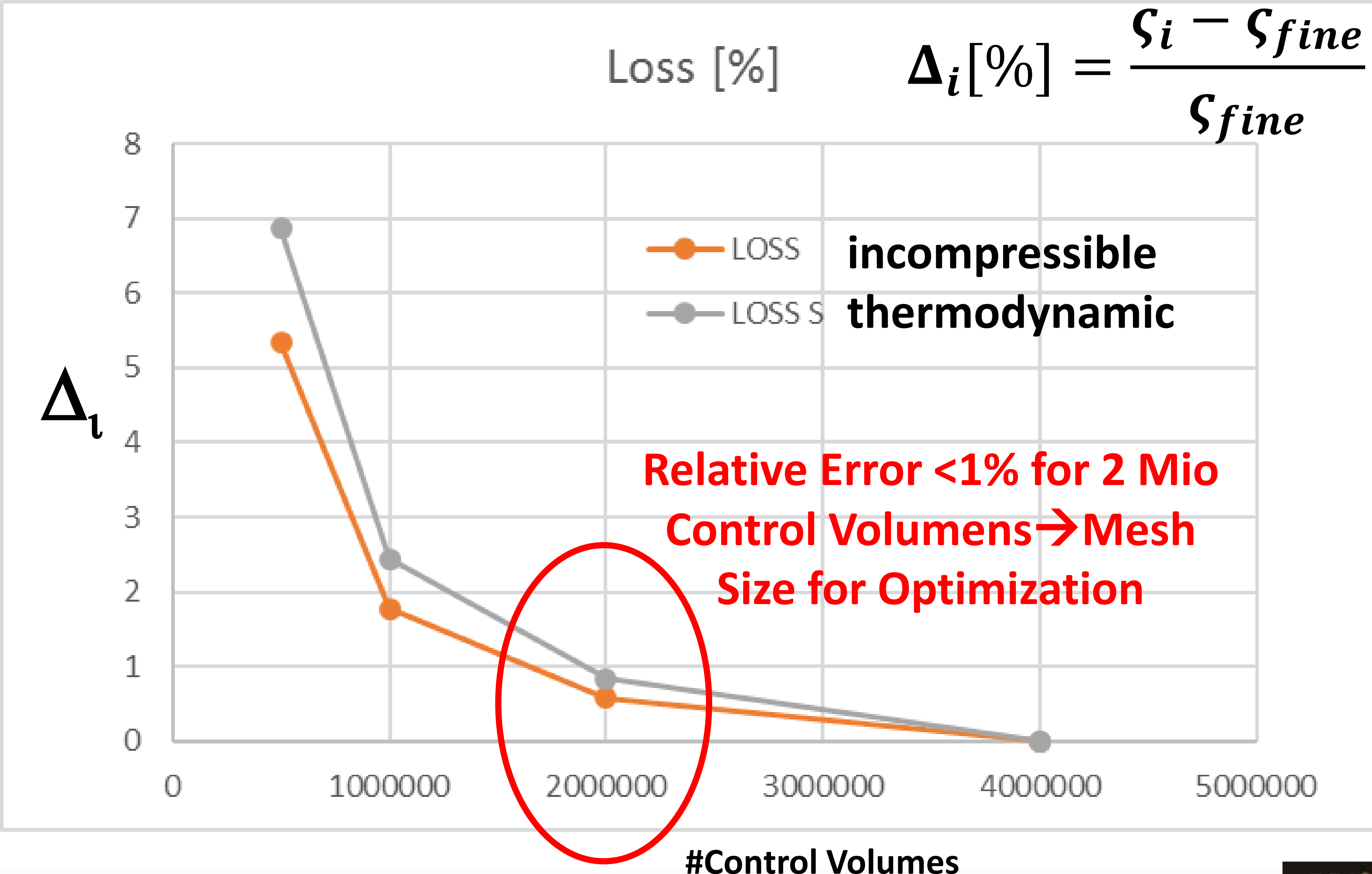
s0 = massFlowAve(Static Entropy)@Inlet
Entropy = (Static Entropy-s0)/R
Loss S = massFlowAve(Entropy)@Outlet

<u>Flow Angle @ Outlet:</u>

Flow Angle = atan2(Velocity Circumferential,Velocity w)
DirOut5 = areaAve(Flow Angle)@Outlet

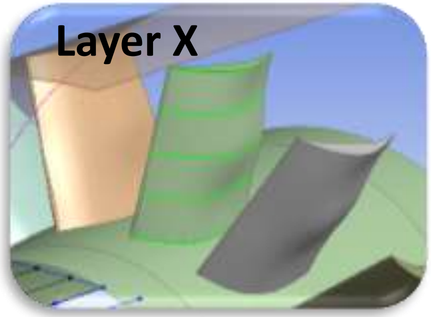
*DirOut4=sum(((Velocity Flow Angle -90[deg])*pi/180[deg])^2)@Outlet*
sum: wrt to number of nodes @ Outlet!

CFD, Mesh Study

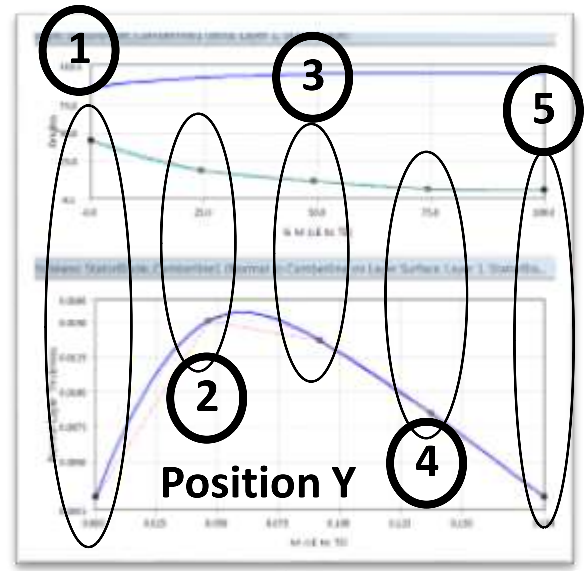


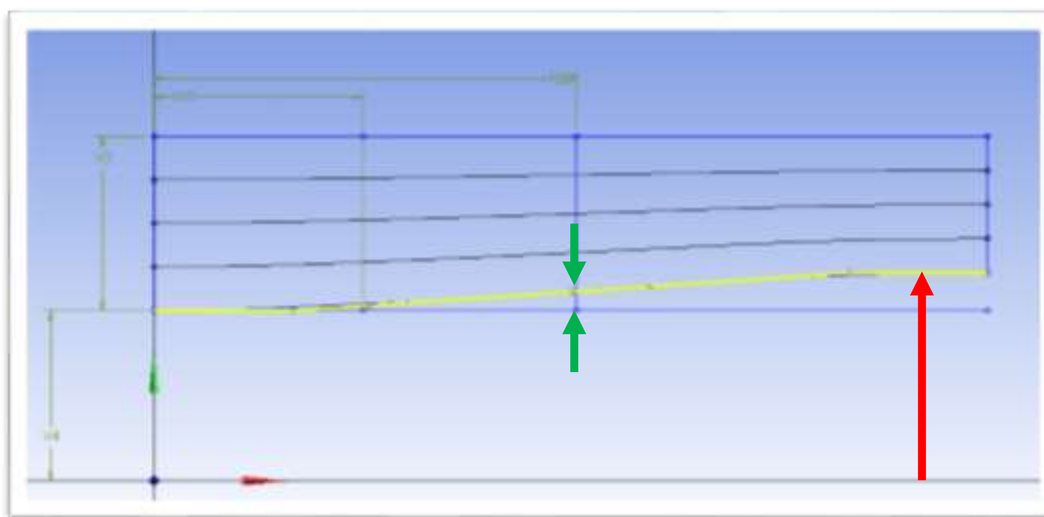
Parameter Space

- Input Parameter
  - DeltaBetaXY [-5°; +5°]
    - Layer X, Position Y (1-5)
  - DeltaThicknessXY [-0.001; 0]
    - Layer X, Position Y (1-5)
  - Hub Radius @ Outlet
  - Hub Radius Relative @ TE
  - Ellipse Ratio, LE/TE Hub&Shroud
- Total 56 Parameter
- Output Parameter:
  - Loss
    - incompressible
    - thermodynamic
  - Flow Angle

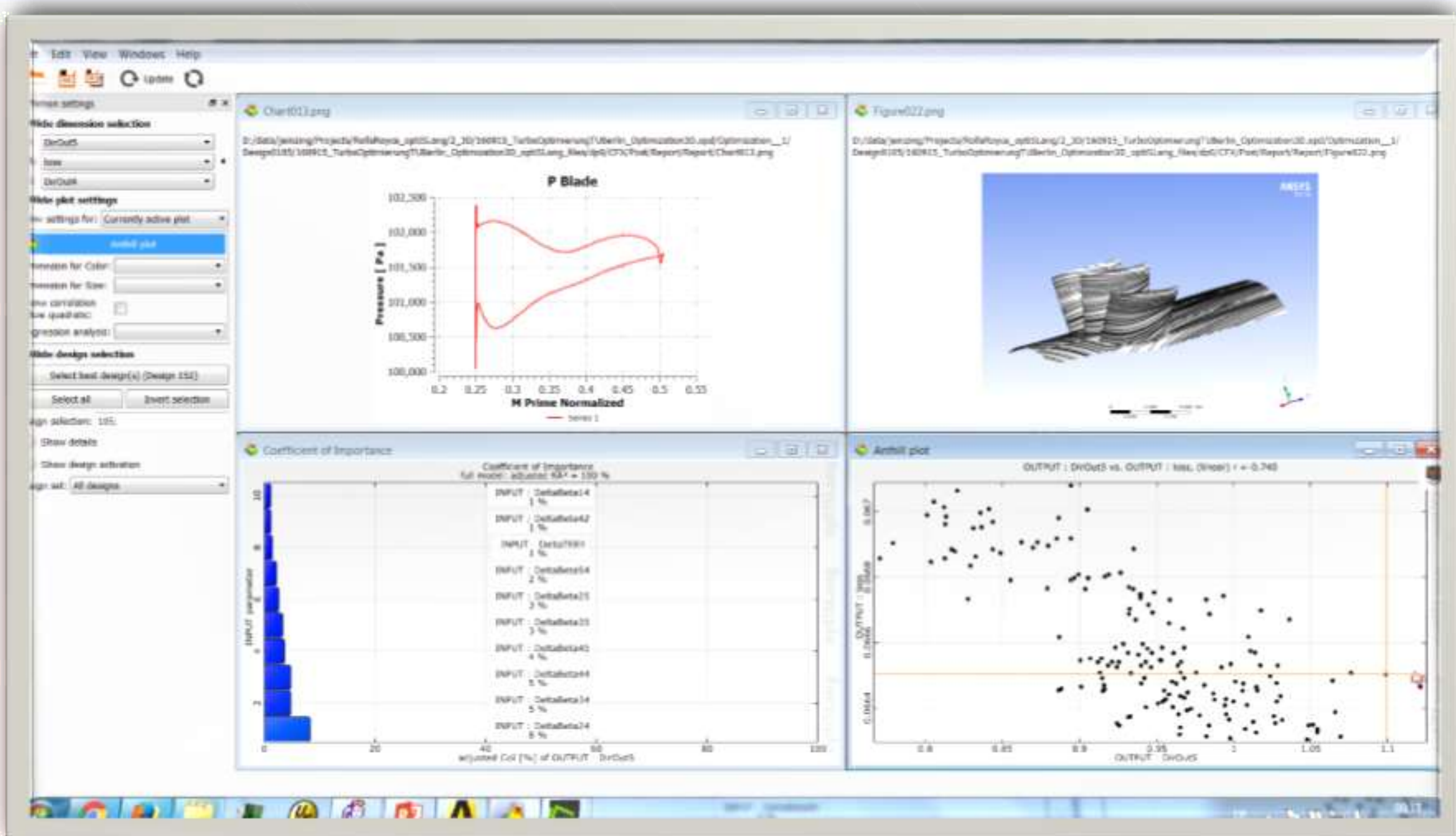


Delta wrt to pre-optimized 2D design





Sensitivity Analysis – Monitoring

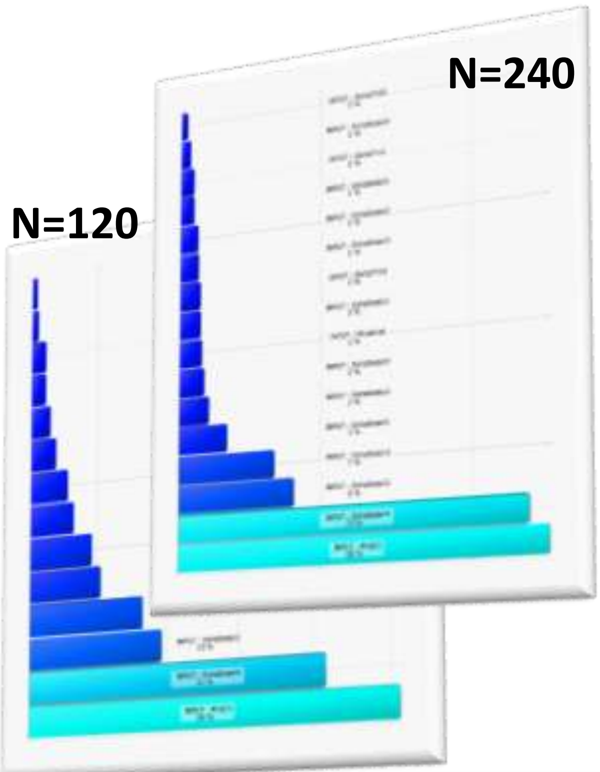


Sensitivity Analysis - Summary

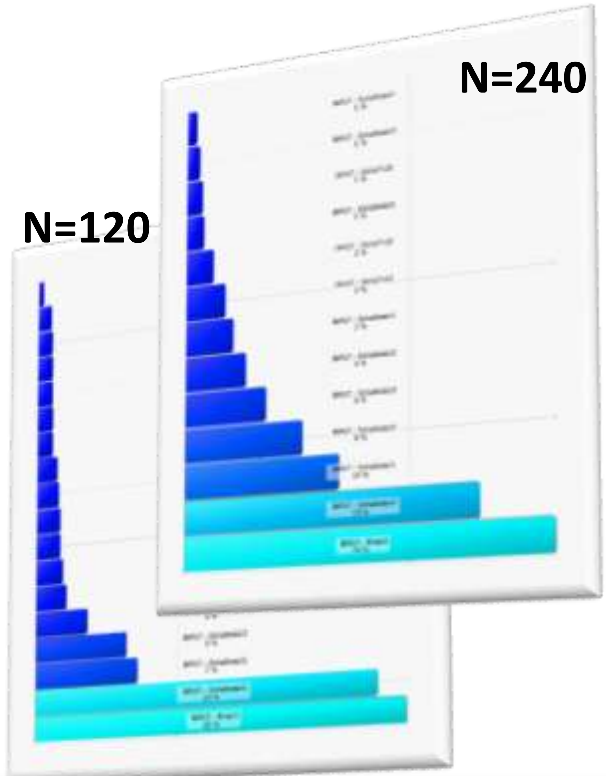
CoP = f(#Designs)	120	240
Loss incompressible	80	80
Loss thermodynamic	79	81
Flow Angle	96	96

Conclusion:

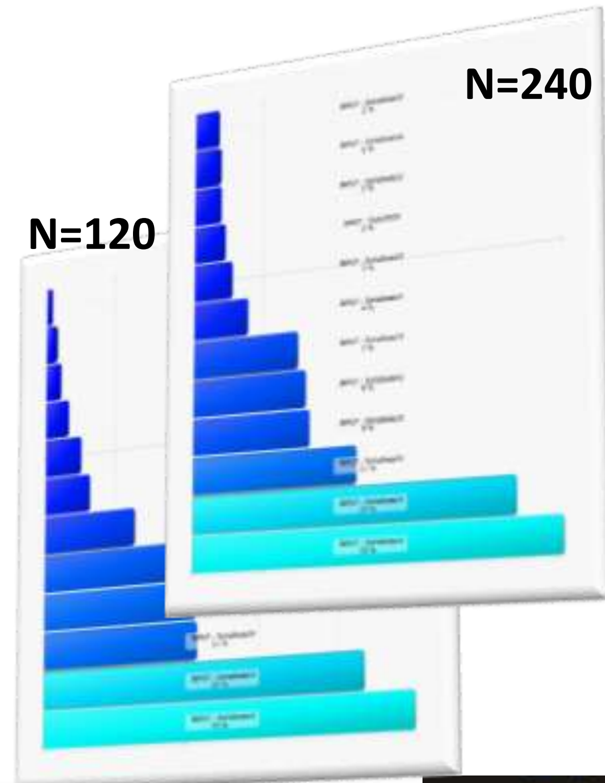
- **CoP small increase**
- **Important Parameters: small change**
- **2 dominating Parameter per Output**



Loss incompressible

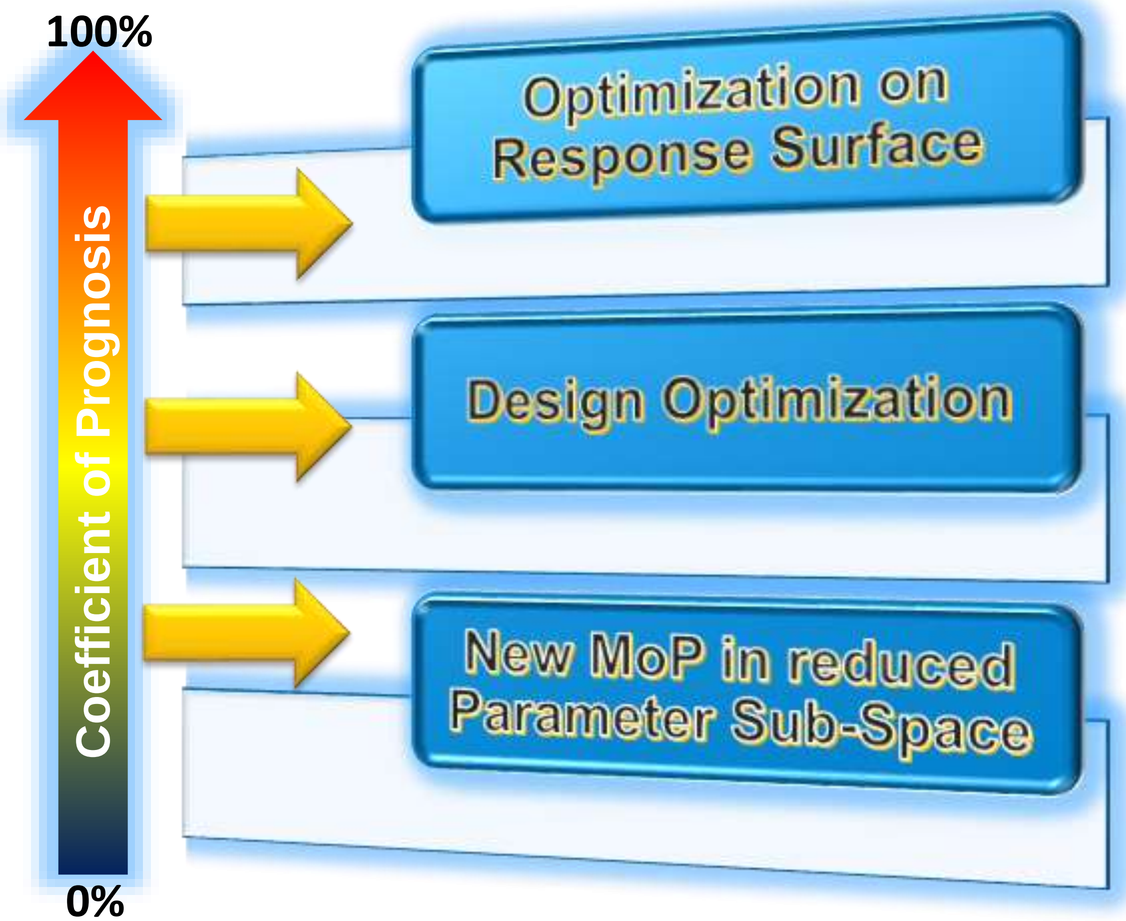


Loss thermodynamic



Flow Angle

Sensitivity Analysis – next Step



NO: CoP too small (<90%)

YES: with important or dominating parameters only!

YES: in Reduced parameter Space, wrt to dominating parameter!

→ MoP in Sub-Space was chosen

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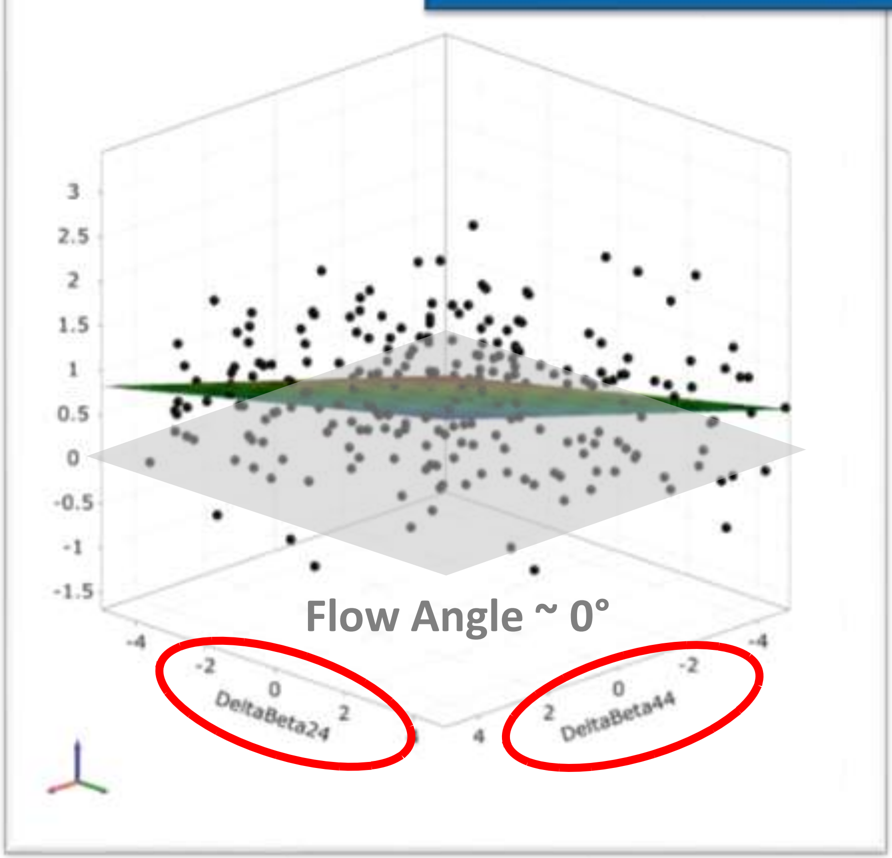
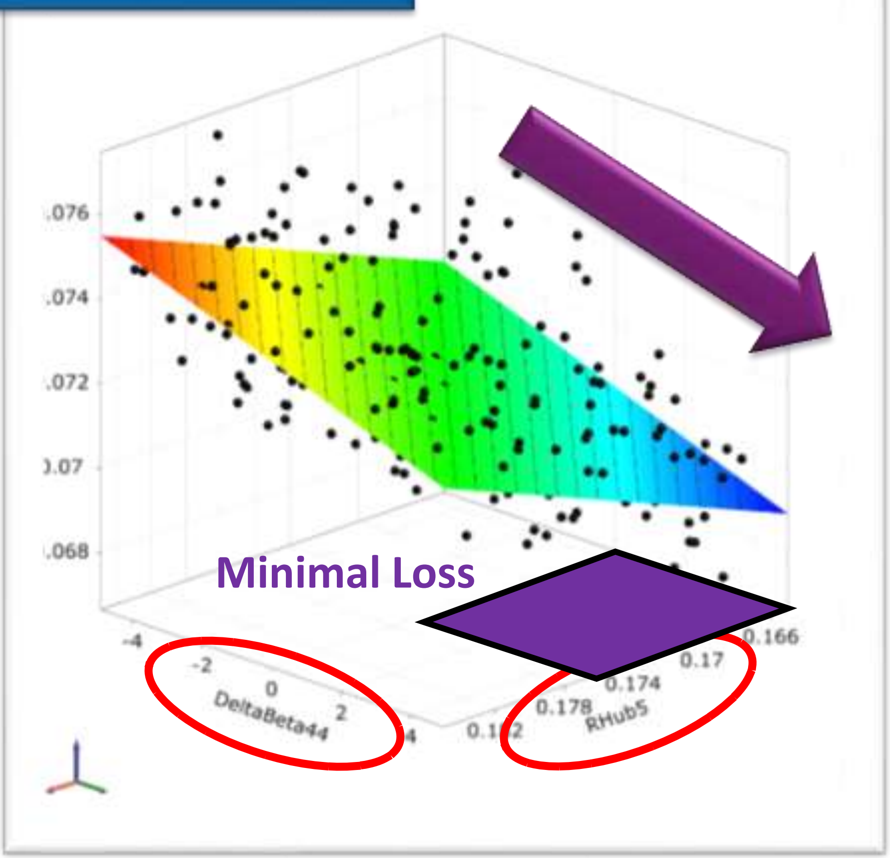
Sensitivity Analysis – Space Reduction

3 dominating Parameters
Min/Max Bounds modified to fulfill Objective
Bounds shifted to Area of Interest

Flow Angle



Loss, incompressible



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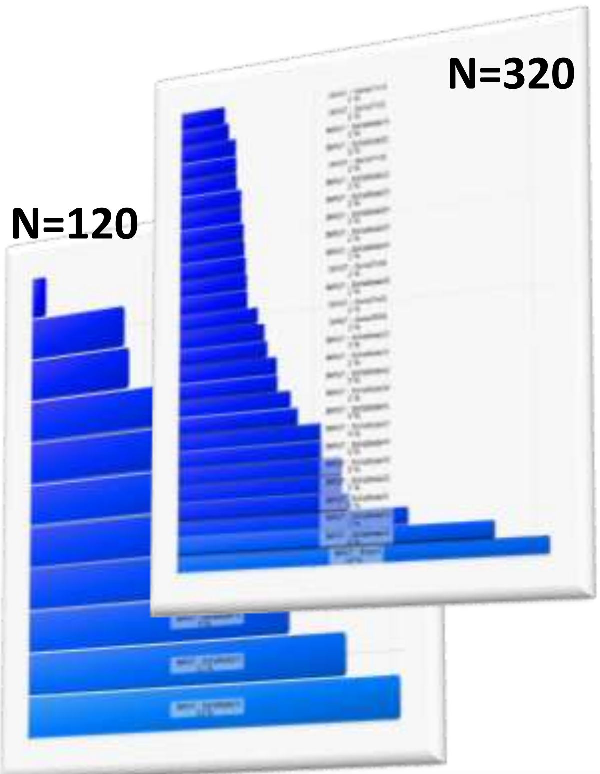
Sensitivity in Sub-Space - Summary

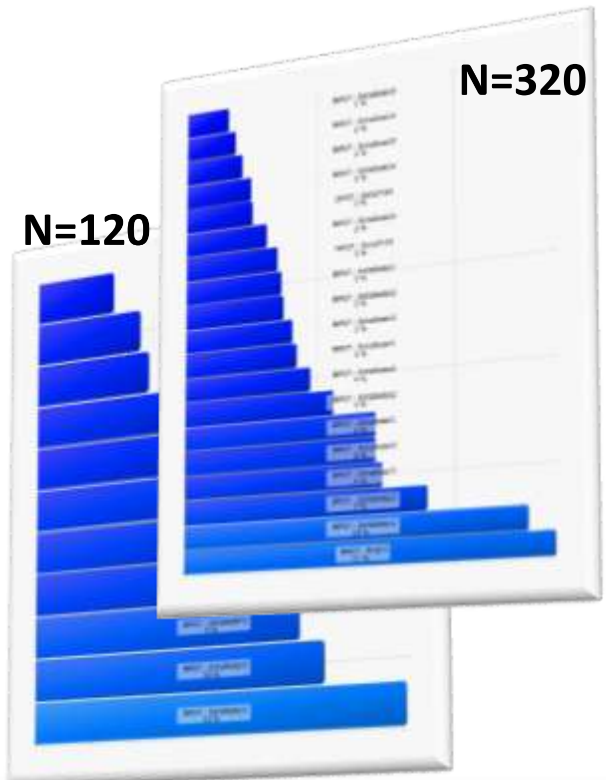
CoP = f(#Designs)	120	320
Loss incompressible	70	70
Loss thermodynamic	68	70
Flow Angle	95	96

Conclusion:

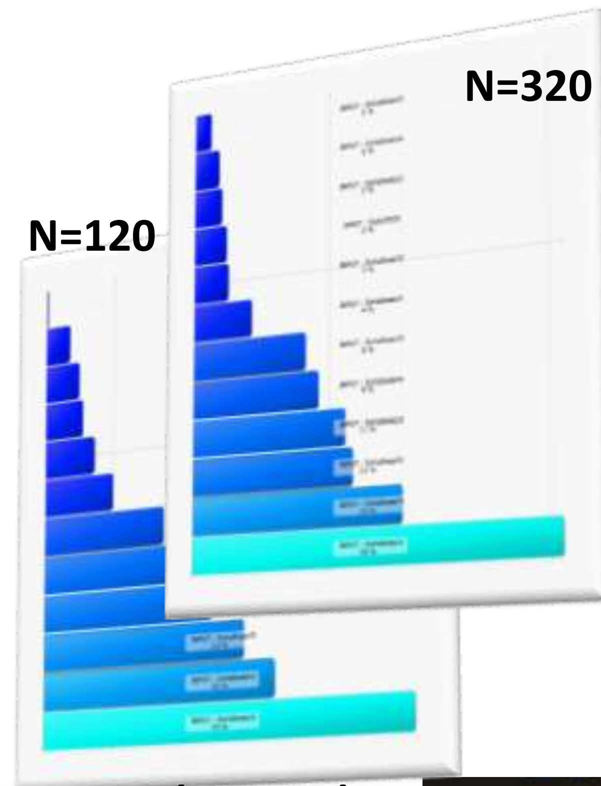
- **CoP small increase/decrease**
- **Important Parameters: increase**
- **High dimensional MoP!**



Loss incompressible



Loss thermodynamic

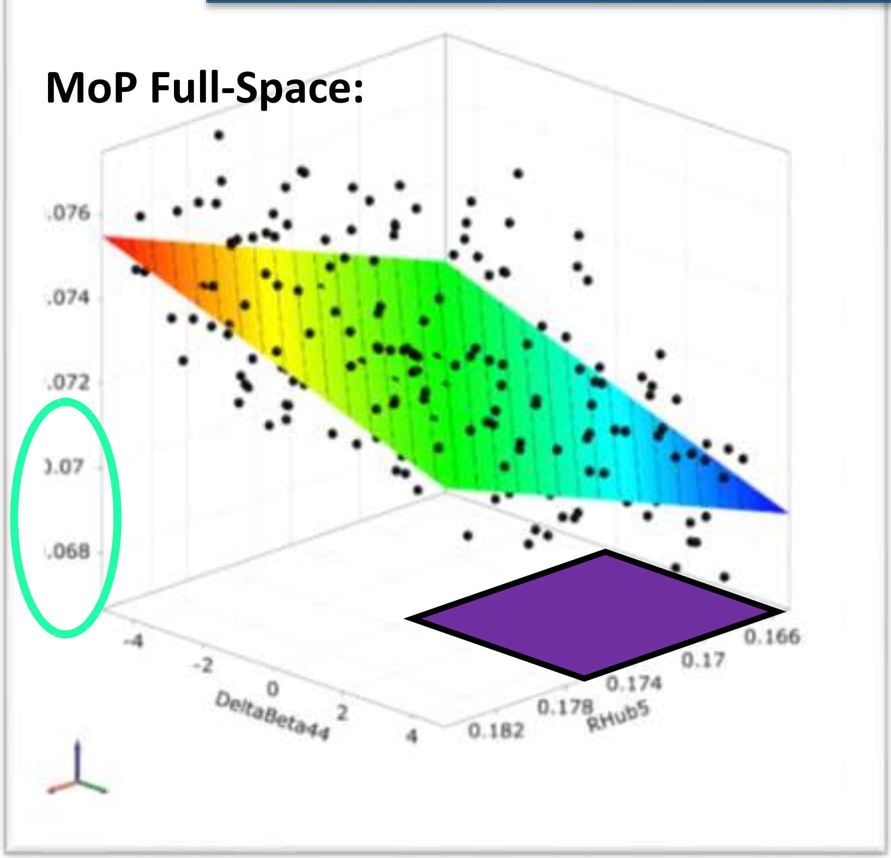


Flow Angle

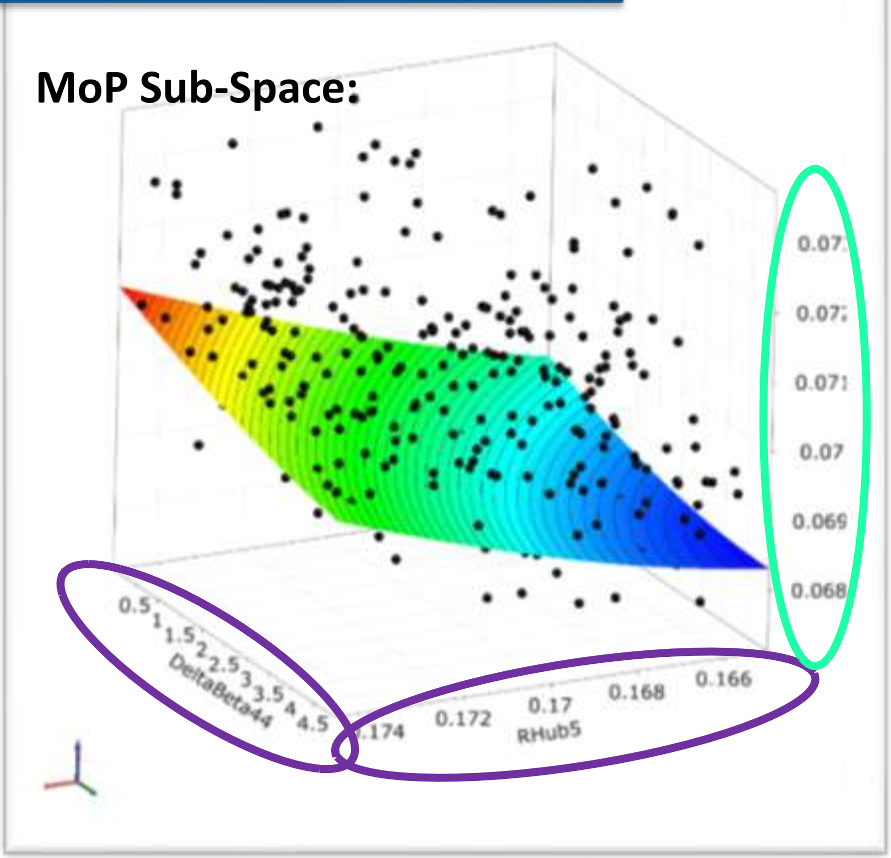
Sensitivity in Sub-Space – Response Surface

Loss incompressible: Full-Space to Sub-Space
- **Visual: “refined area, with additional curvature”**
- **Sub-Space is high dimensional, medium CoP**

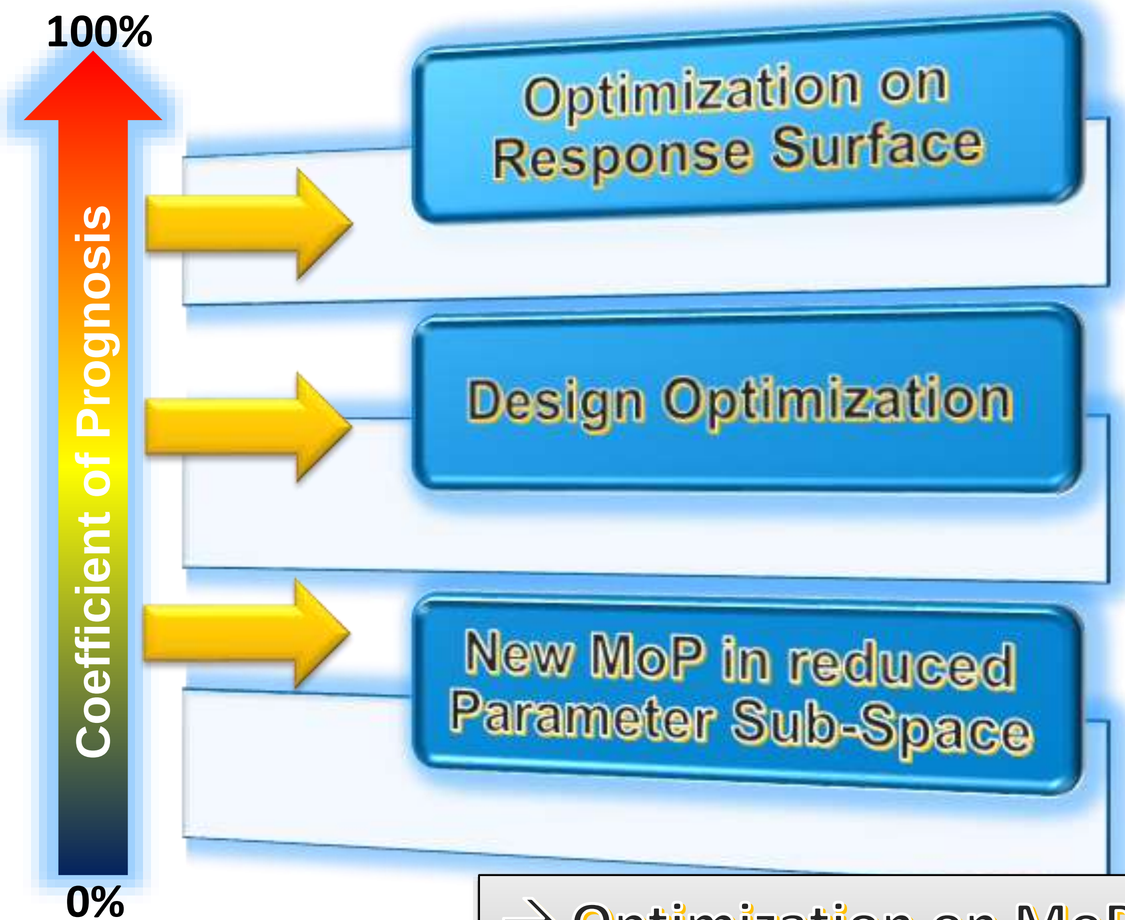
MoP Full-Space:



MoP Sub-Space:



Sensitivity in Sub-Space – next Step



**NO: CoP too small (<90%)
Use Anyway → FAST**

YES: with important or parameters only!

High dimensional MoP → high CoP too expensive!

→ Optimization on MoP
→ Design Optimization

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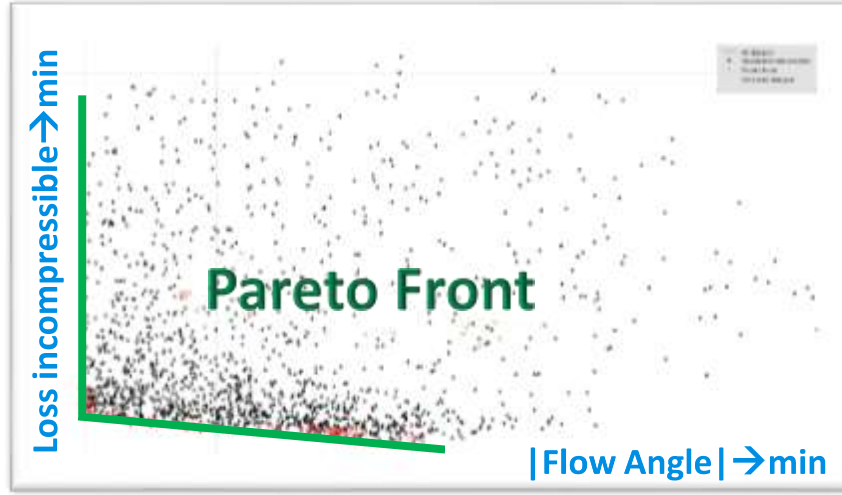
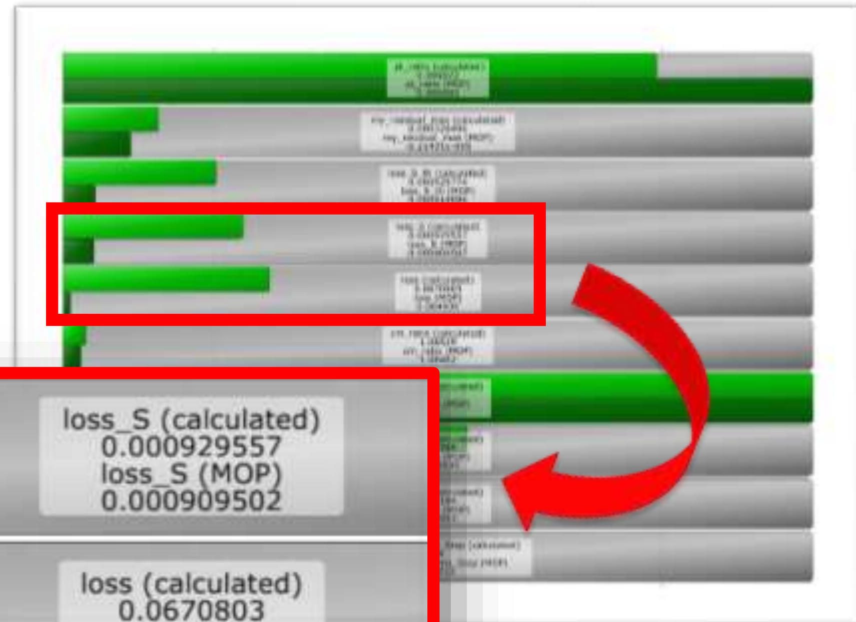
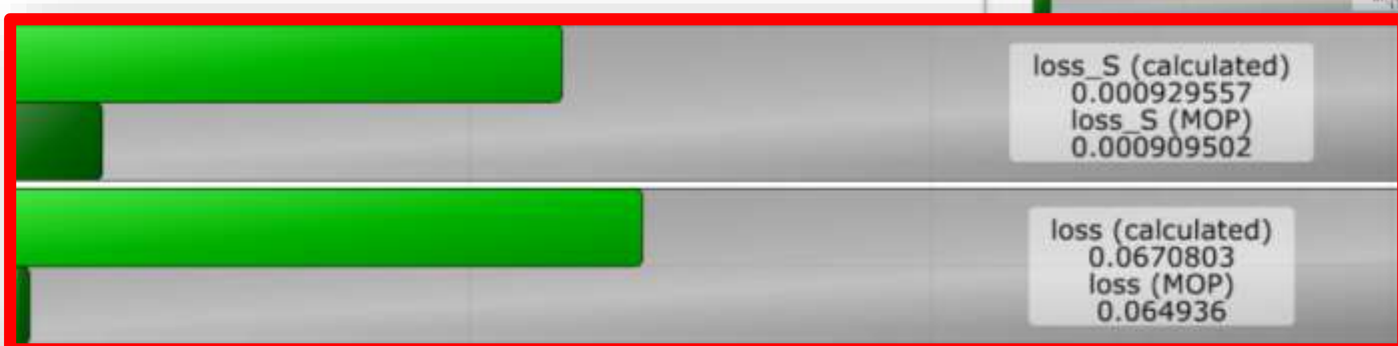
Design Optimization – on MoP

- Pareto Optimization=expensive!
- Optimization Conflict?
  - Loss→min
  - |Flow Angle|→min
  - Yes, but week
- Optimization on MoP=FAST!
  - Used, even with medium CoP
  - MoP Prediction has medium Quality, due to medium CoP!







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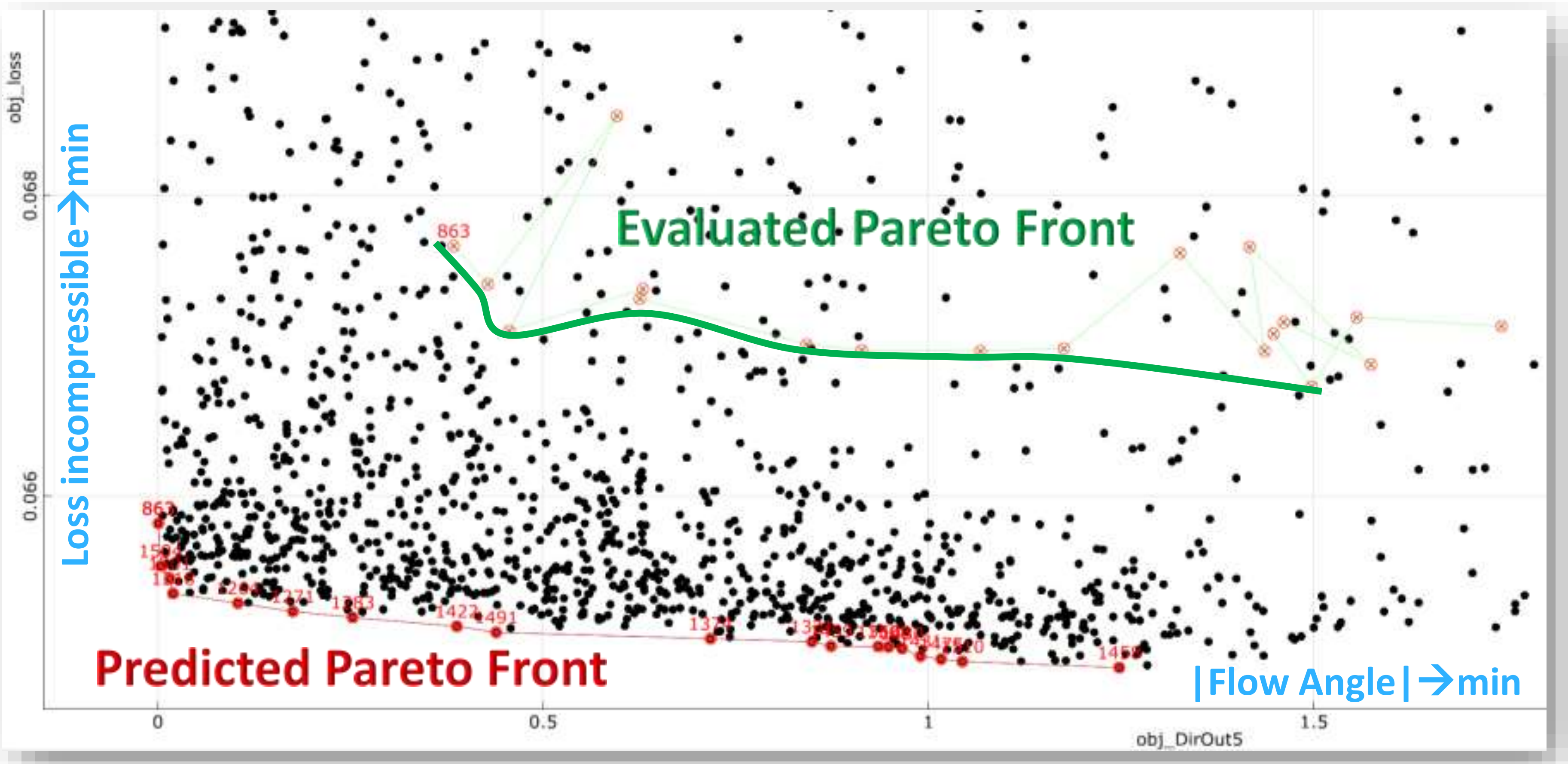
Design Optimization – on MoP

Quality of Prediction is medium → Design Optimization required
Weak Conflict between objectives → Single Objective Optimization → faster



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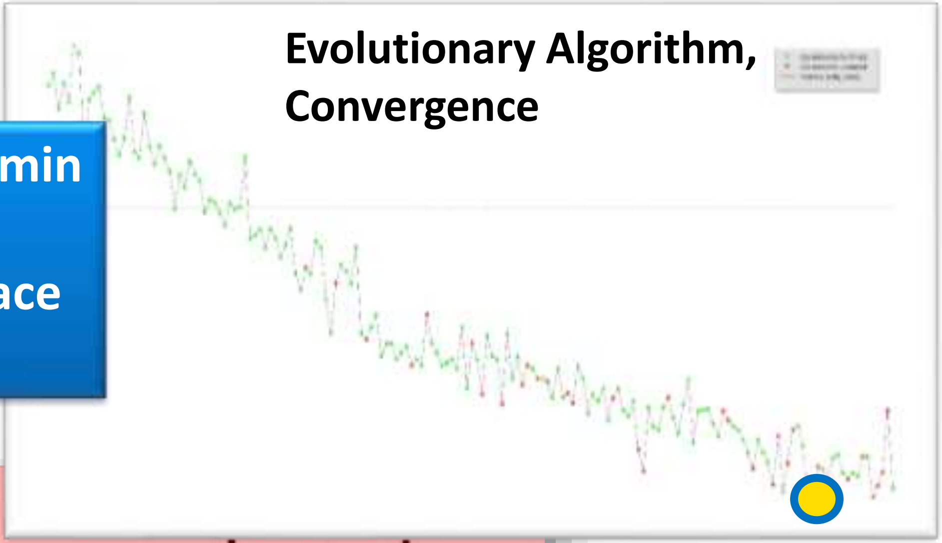
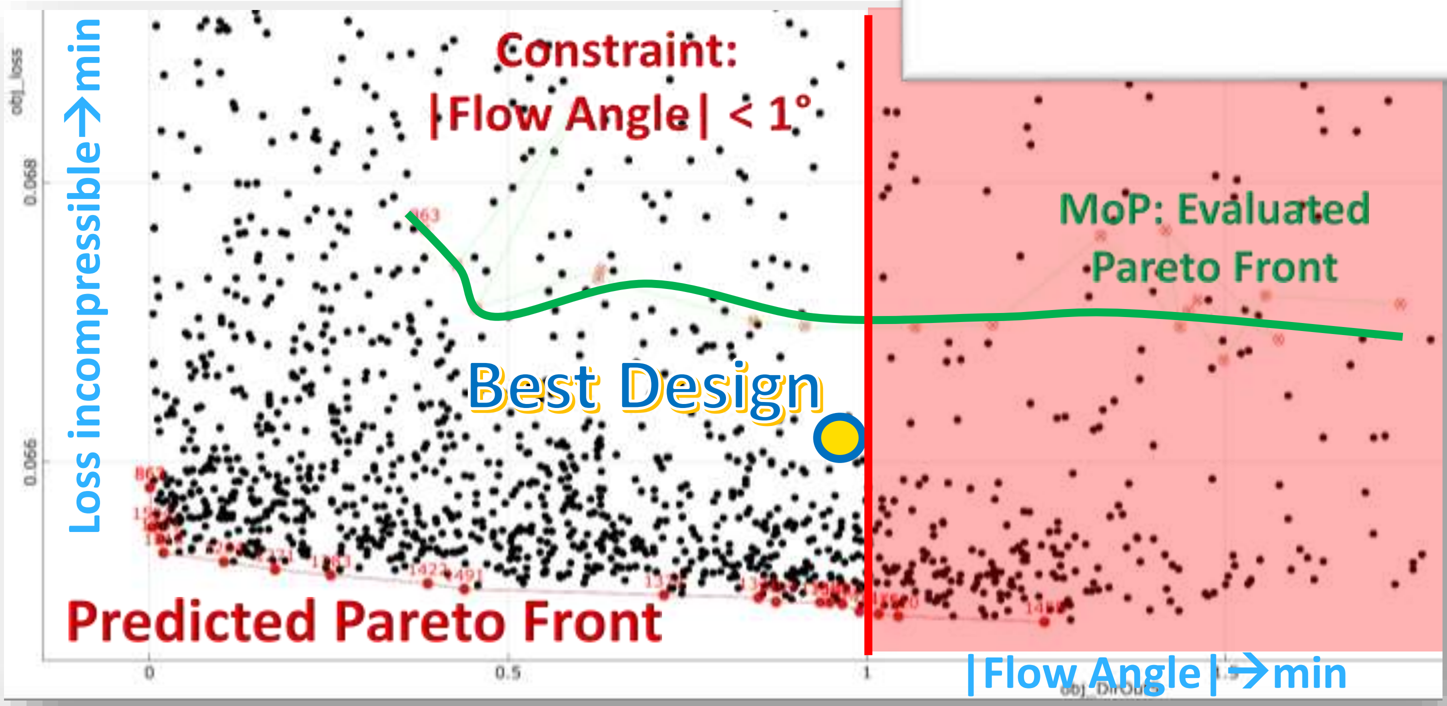
Design Optimization – on CFD

Single Objective Optimization> loss → min
Constraint: |Flow Angle| < 1°
All important Parameter from Sub-Space
Meta-Model included





Design Optimization – Summary

All Results wrt to Parameter Space!

Meta-Model:
→ Improved Design
→ "Area of Interest"
→ Important Variables

Design Optimization:
→ Further Improvement
→ More efficient due to
  → Important Variables
  → "Area of Interest"

Knowledge Gain →

	Initial Design	Meta-Model Prediction	Meta-Model Evaluated	Design Optimization	Δ Initial vs Optimized
Loss incompr. [%]	**6.92**	6.49	6.71	**6.63**	**-4.2%**
Loss therm. [1e-3]	**0.961**	0.909	0.929	**0.919**	**-4.4%**
Flow Angle [°]	**3.49**	0.989	1.45	**0.998**	**-2.5°**
#Designs	**1**	320	1	**169**	

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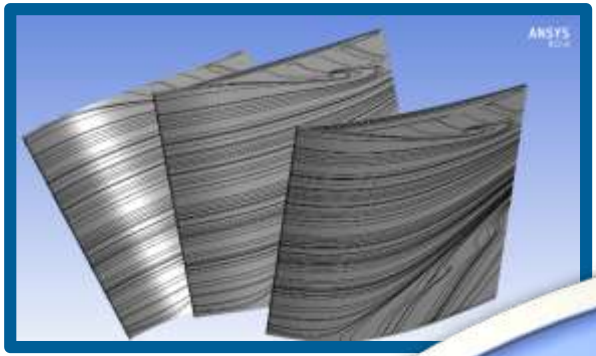
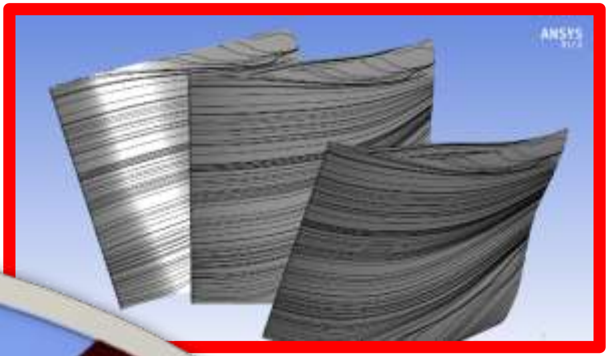
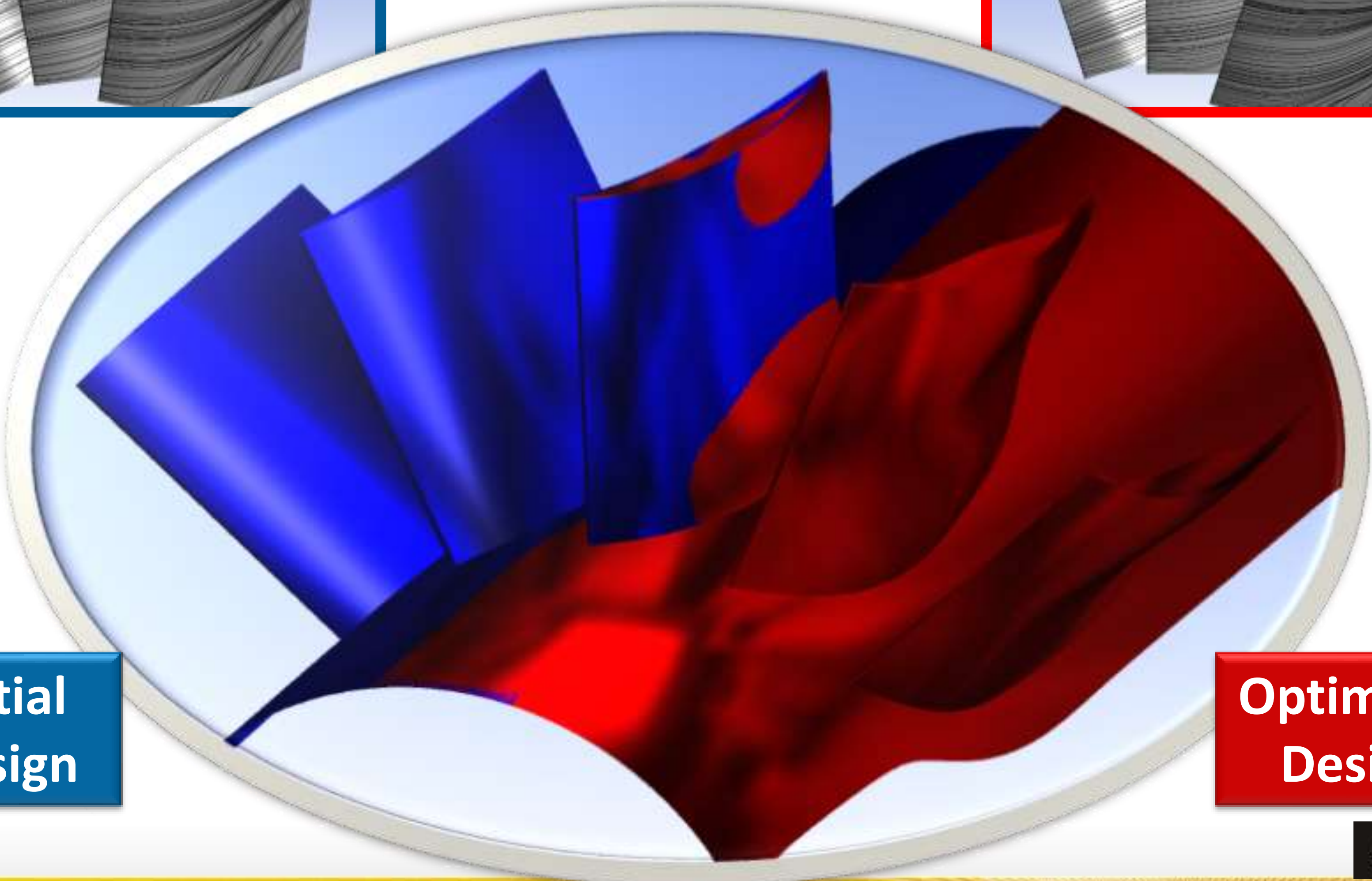
Design Optimization – Result





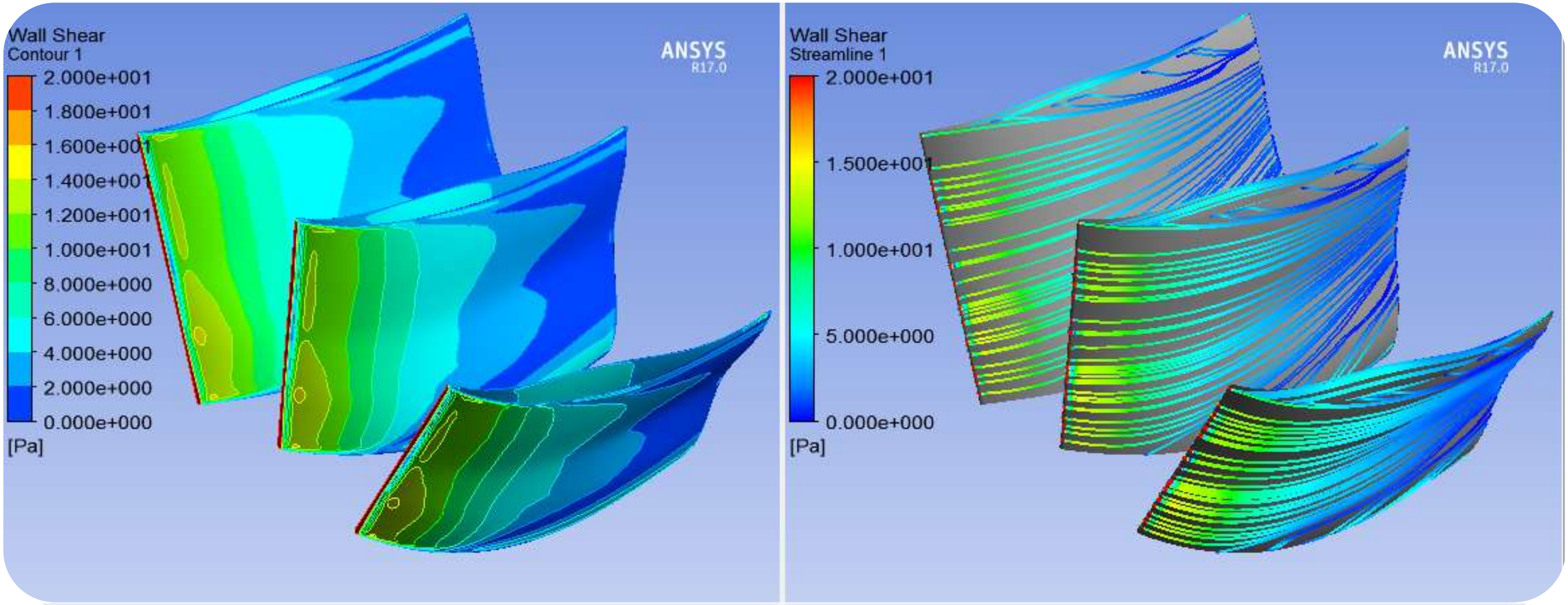


Initial Design

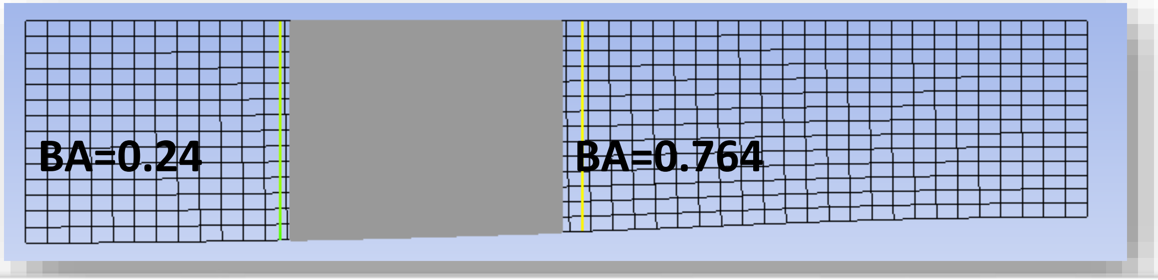
Optimized Design

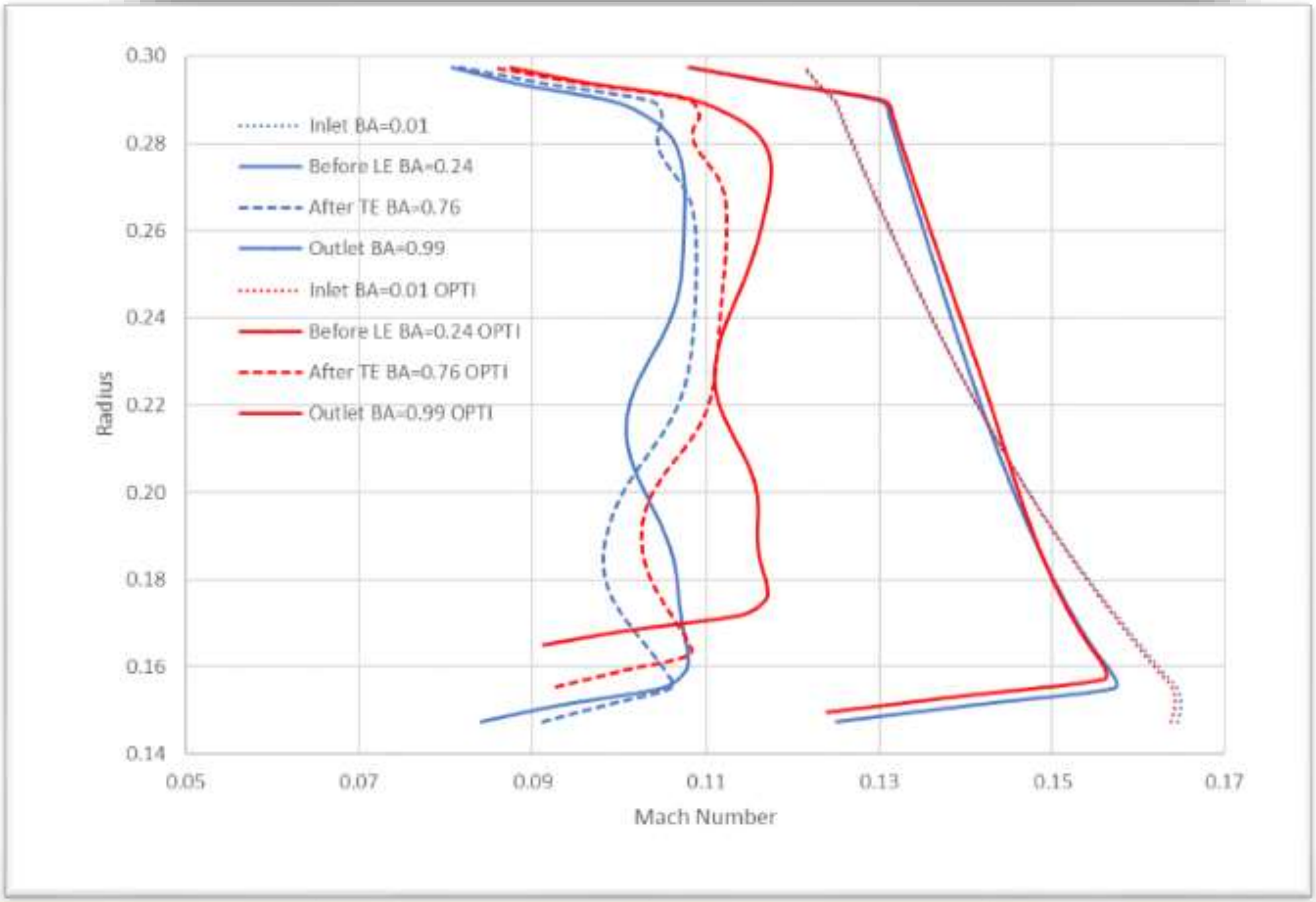
Design Optimization – Outlook

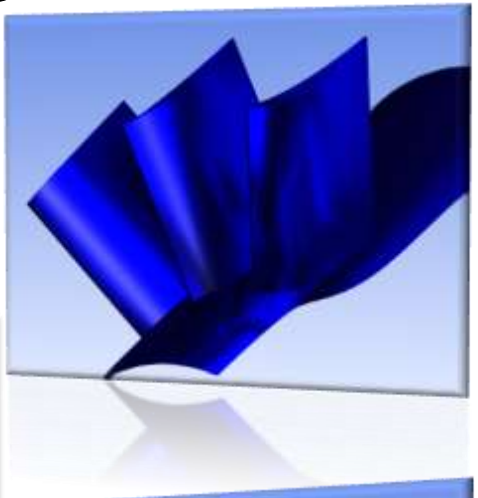
Recirculation could not be removed in defined Parameter Space
→ Review Parameter and Limits to avoid recirculation



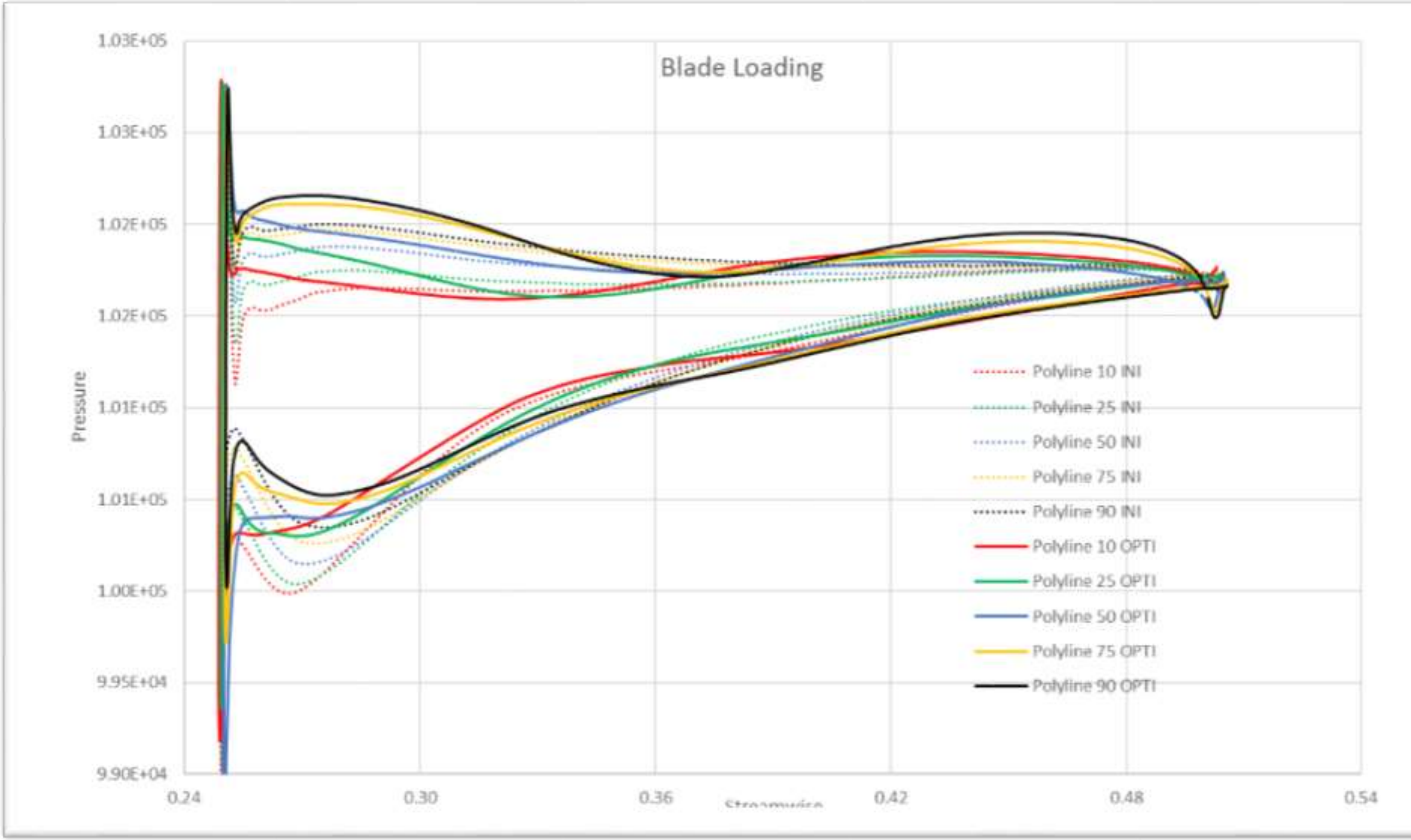
Design Optimization – Velocity Profile







Design Optimization – Blade Loading

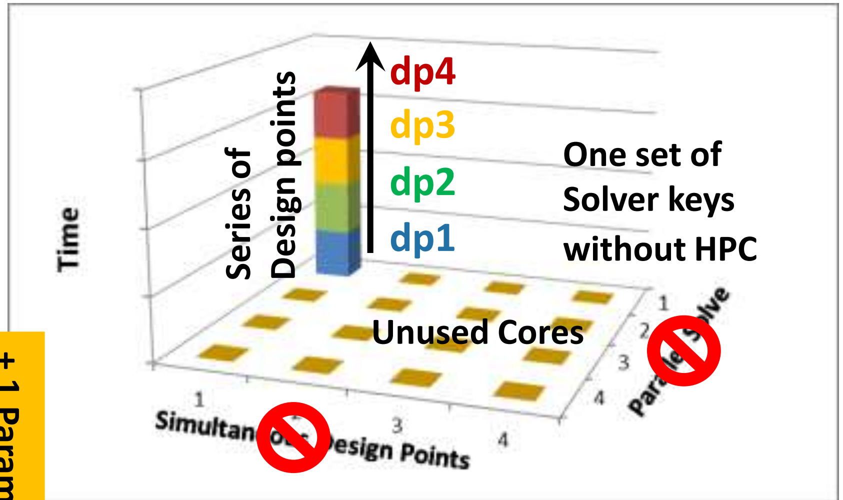


ANSYS

Summary & Outlook

- Summary
  - GUI supported Optimization Process
  - Full Meta-Model delivered:
    - important Parameters
    - "Area of Interest"
  - Sub-Space Meta-Model
    - Design Improvement
  - Design Optimization
    - Further Improvement
- Outlook
  - Double check initial:
    - Parameterization
    - Parameter Bounds
  - Forward Convergence Study of Meta-Model
  - Extend Workflow with additional operating Points

Optimization and HPC Pack License



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