ANSYS

Sensitivity Analysis of a Turbo Compressor with Physical Parameterization

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Turbo Optimization Strategies with Meta-Model

Traditional Design/Optimization Strategy

- Primary Design (Empiric)
- Manual Improvement, CFD
- optiSLang – **small Parameter Range**

Works excellent, since
Engineer + optiSLang = perfect Combination
Key: **small Parameter Range**
Draw back: needs to be done for each new Design

"Optimization does it all"

- Primary Design (Empiric)
- optiSLang – large Parameter Rang

Strategy usually fails, bad Results
Problem: **large Parameter Range**
Benefit (if it works): investment upfront, fast Optimization for each new Design

Agenda

- Turbomachinery Design Principals
- Traditional Parameterization and Limitations
- Physical Parameters
- Sensitivity Analysis

Turbomachinery – Conservation Principals

Mass Conservation $$\sum \int \underbrace{\rho \vec{c} \vec{n}}_{\dot{m}} \, dA = 0$$

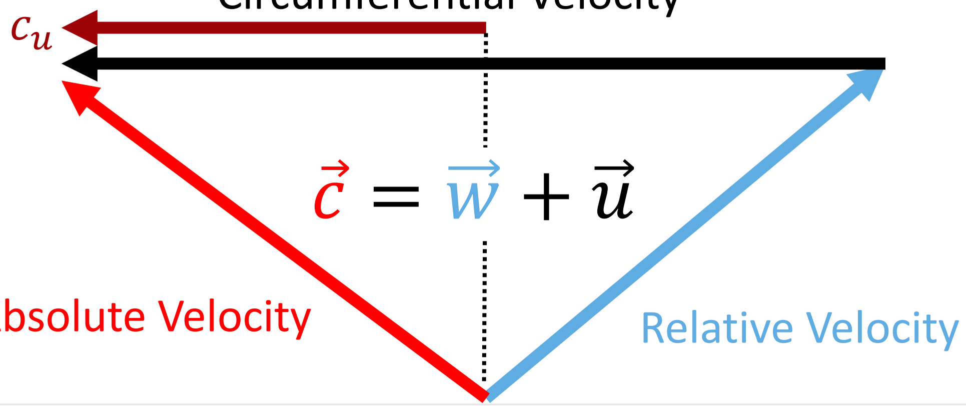
Momentum Conservation $$\sum \int \underbrace{(\rho \vec{c} \vec{n})}_{\dot{m}} \, \vec{c} dA = \sum \underbrace{\int (p \vec{n} + \vec{\tau}) dA}_{\vec{F}}$$

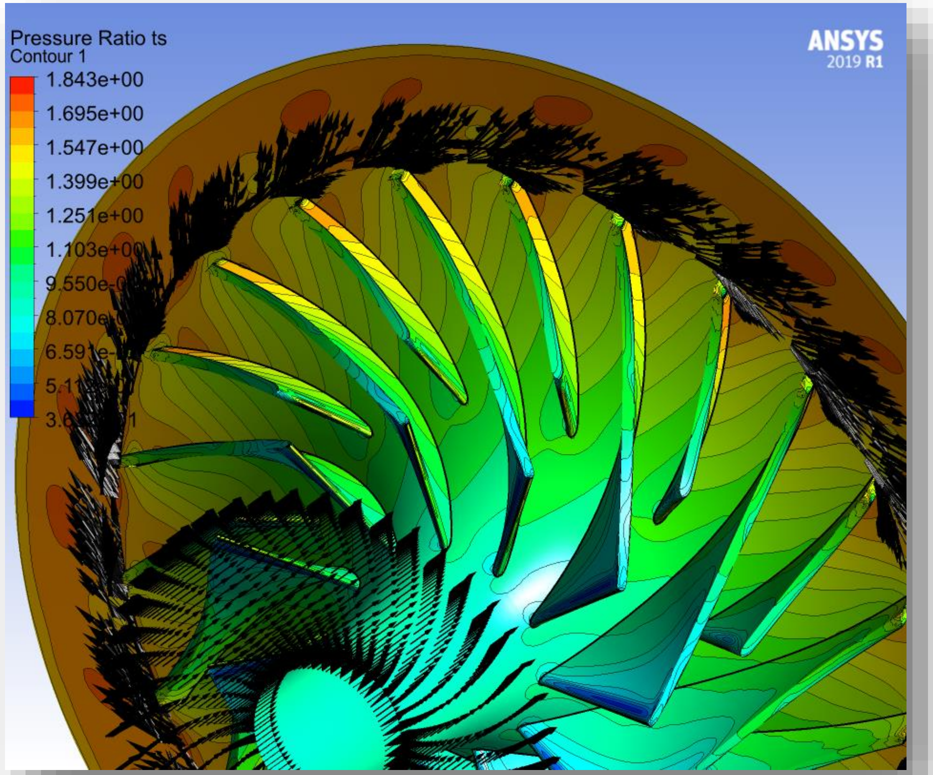
Energy Conservation – Euler Equation

$$\Delta h_t = P_{Mech} + Q_{Therm} \qquad \Delta h_t = \Delta(u c_u)$$

Total Enthalpy Gain = *Work due Rotation*

Kinematics – Velocity Triangle





Thermodynamics, ideal Gas

Equation of State $p = \rho R T$

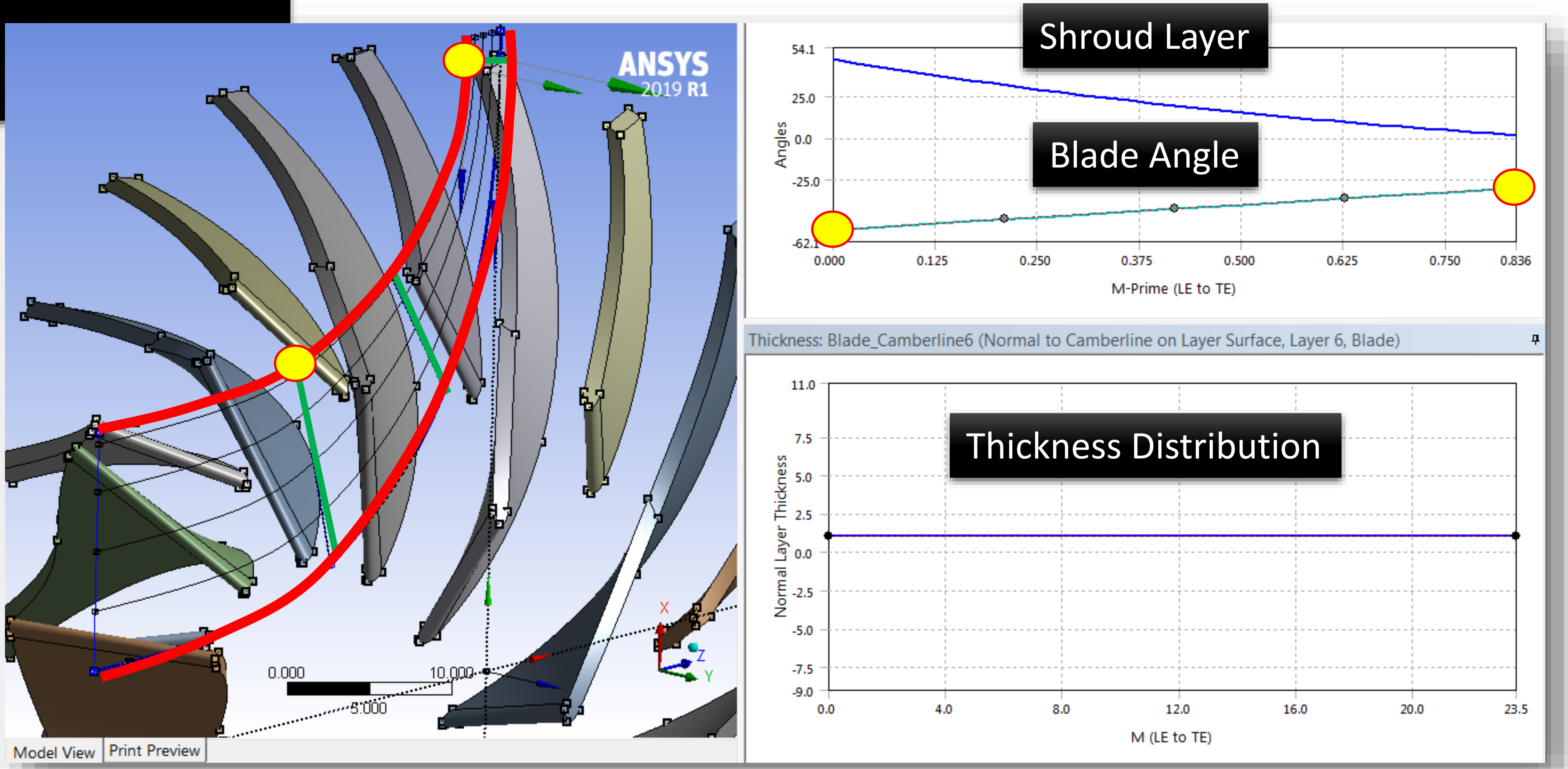
Caloric Equation $h = c_P T$

2nd Law $dh = T ds + \dfrac{dp}{\rho}$

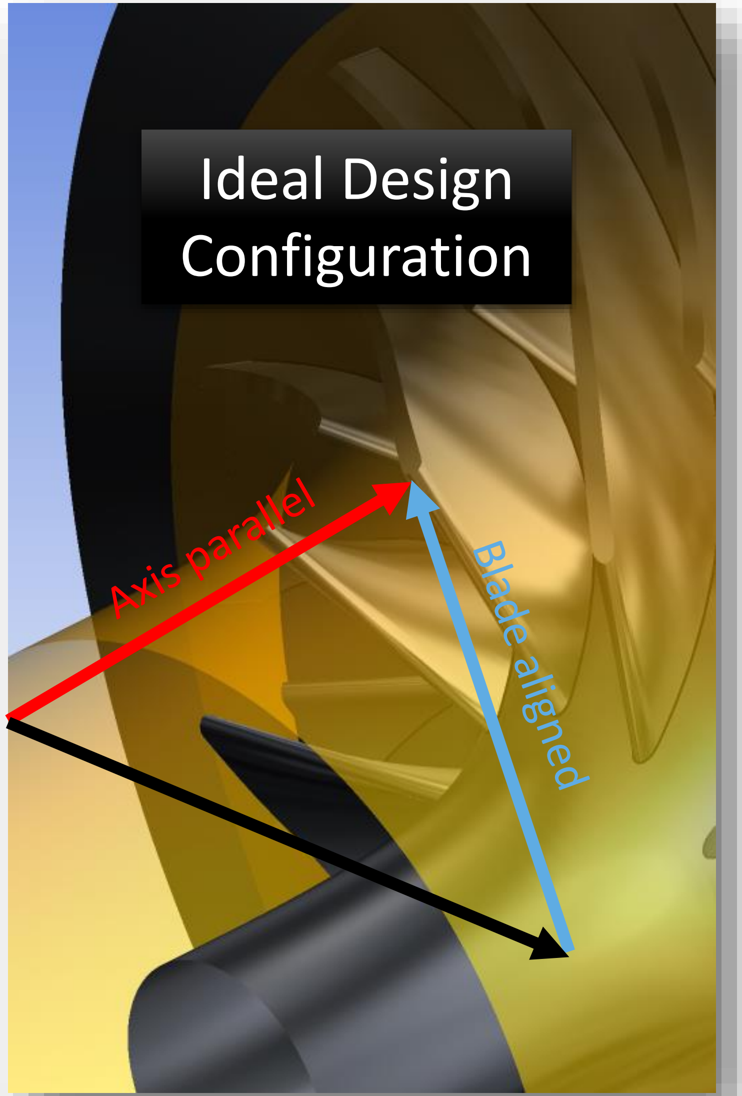
Geometry Parameter

Traditional Turbomachinery Parameterization

- B-Spline for Hub and Shroud
- Line/Curve for Leading- and Trailing Edge
- Blade Angles on n Layers
- Thickness Distribution
- Boundary Conditions



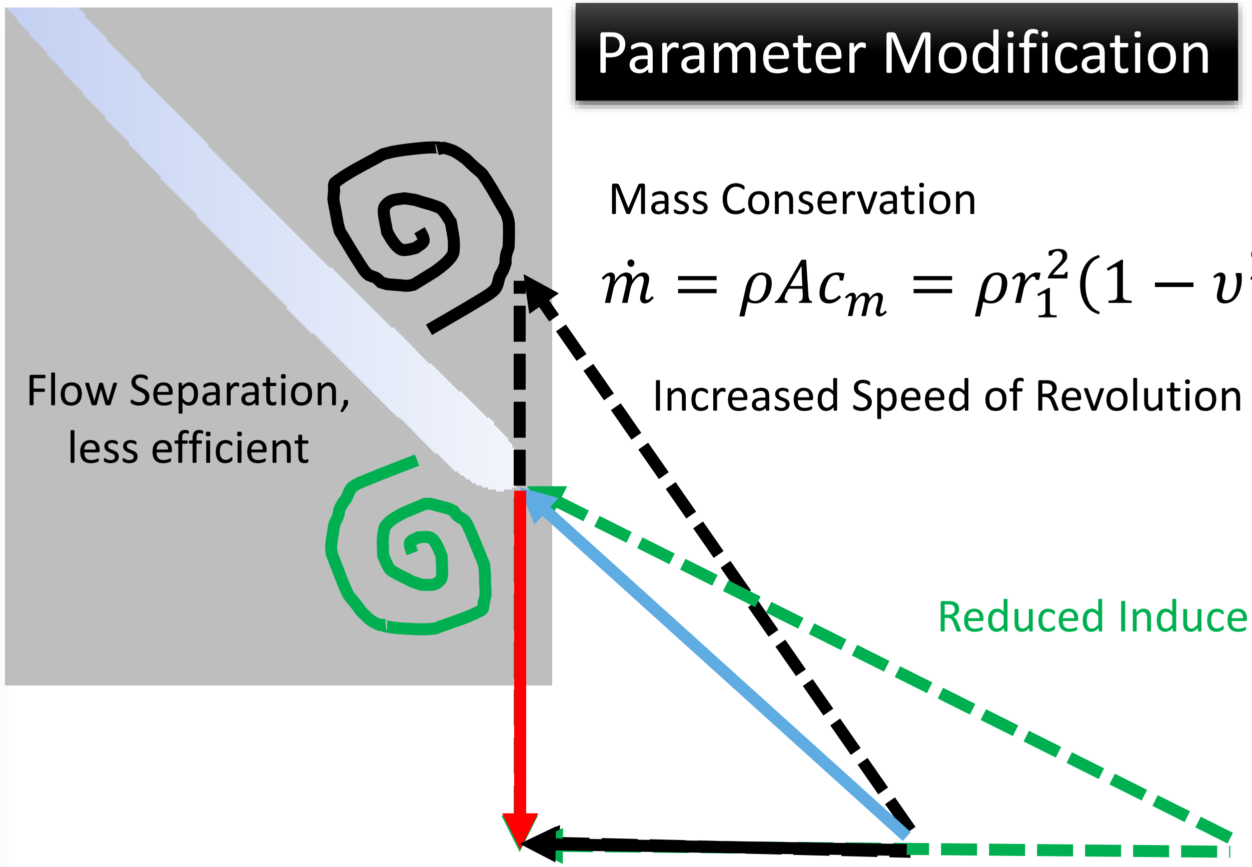
Inducer Geometry



Parameter Modification

Mass Conservation

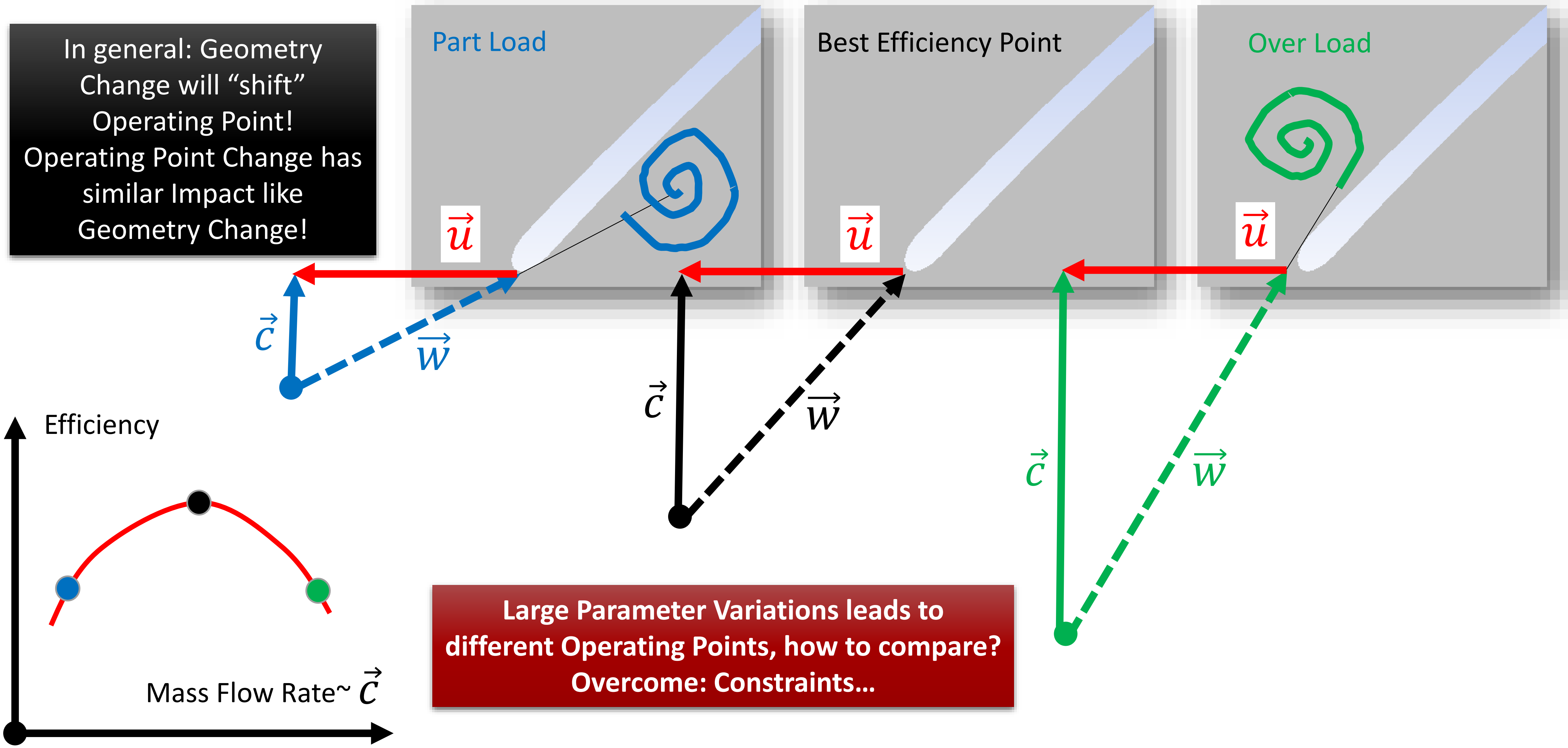
$$\dot{m} = \rho A c_m = \rho r_1^2 (1 - \upsilon^2) c_m = const$$



Large Parameter Variations leads to bad Velocity Triangles
Overcome: Constraints…

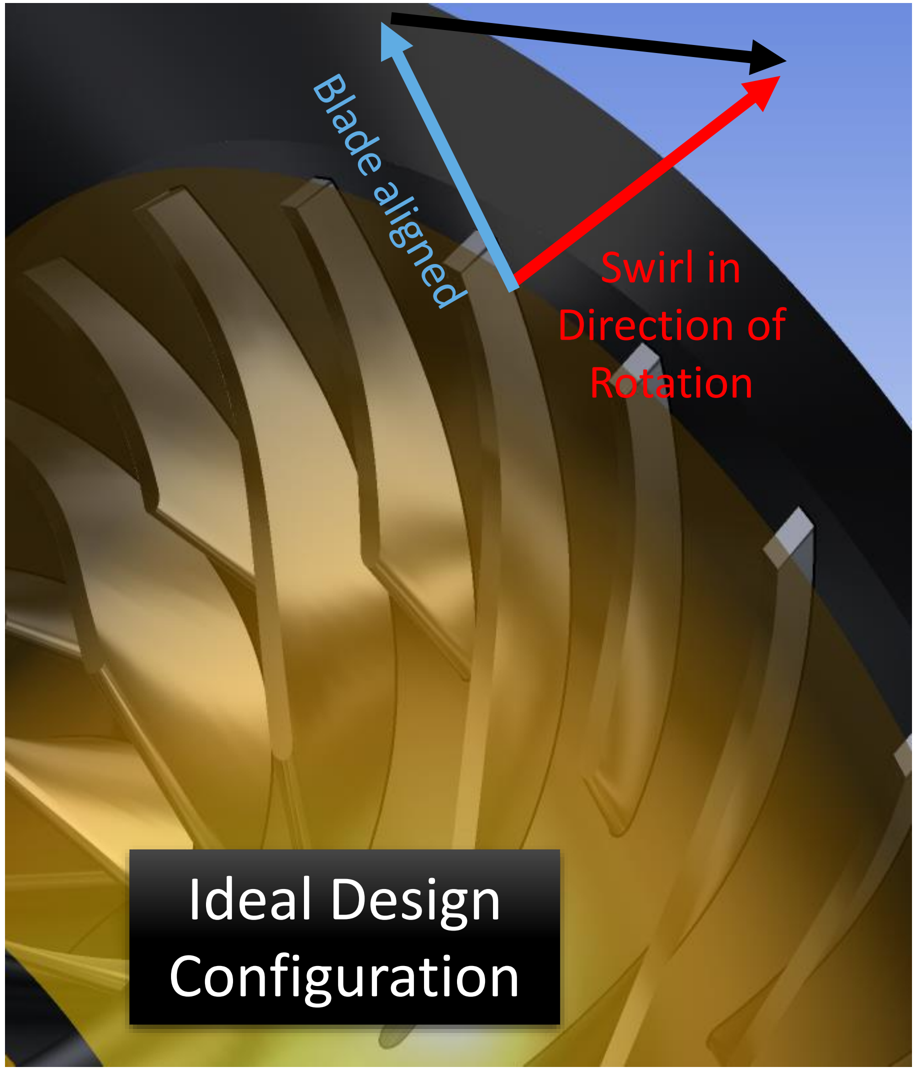
"Hidden" Impact of Geometry Change

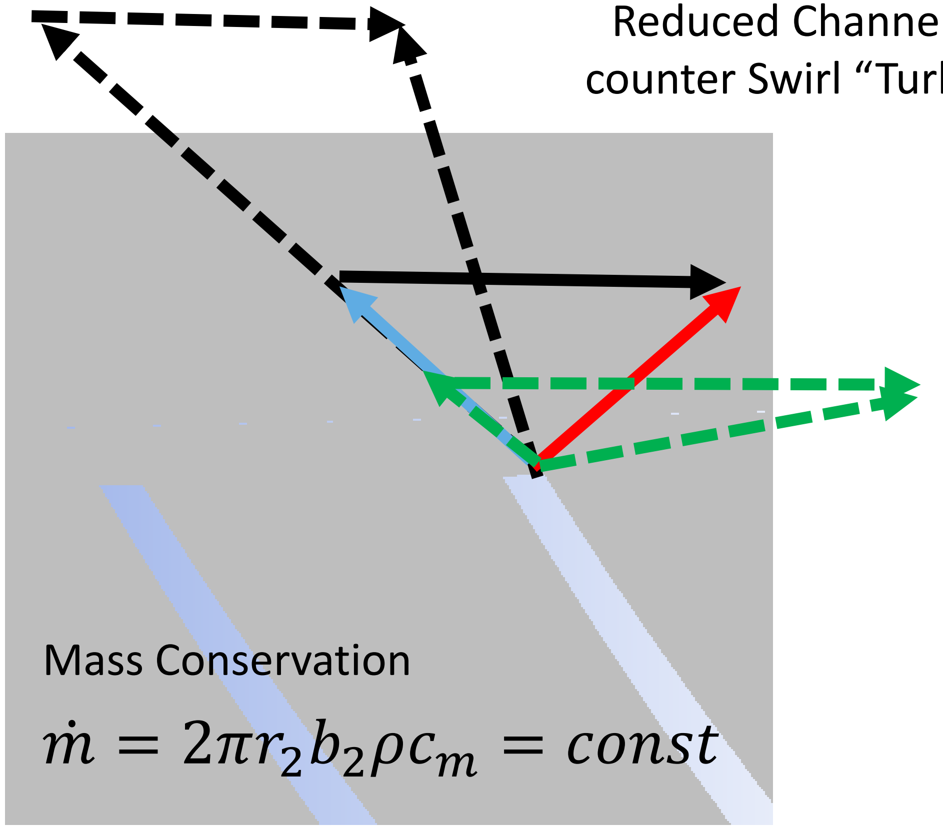
In general: Geometry Change will "shift" Operating Point!
Operating Point Change has similar Impact like Geometry Change!



Large Parameter Variations leads to different Operating Points, how to compare? Overcome: Constraints…

Discharge Geometry





$$\dot{m} = 2\pi r_2 b_2 \rho c_m = const$$

Reduced Channel Hight b_2:
counter Swirl "Turbine Mode"

Increased Impeller Radius r_2:
→ low c_m
→ high uc_u
→ high dp/dr
→ Flow Separation

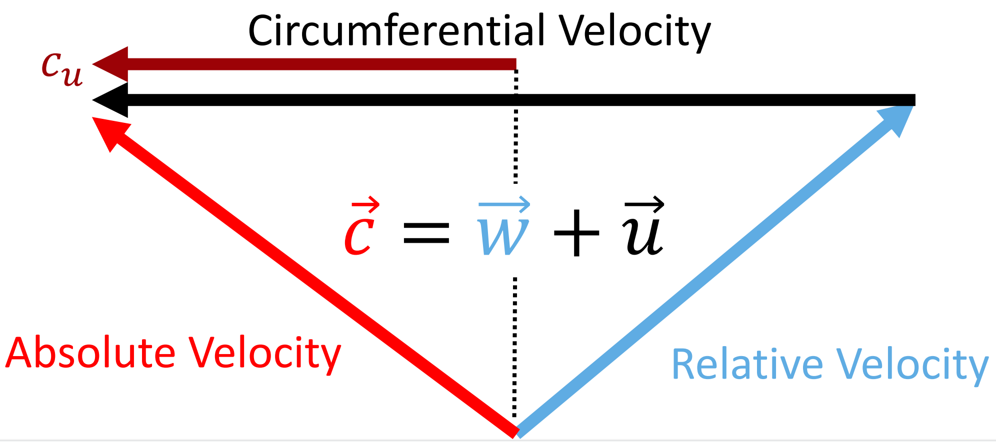
Large Parameter Variations leads to bad Velocity Triangles
Overcome: Constraints…

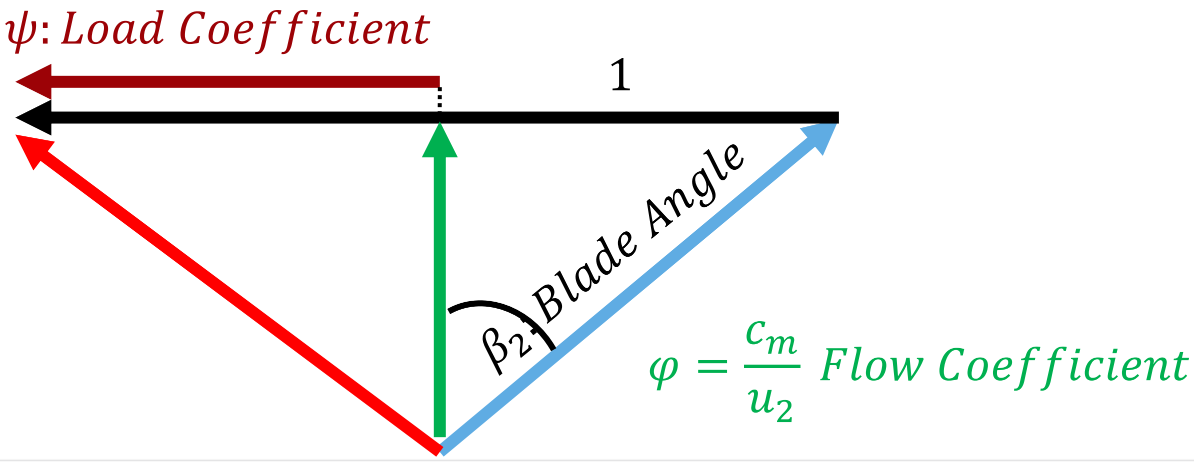
Dimensionless Analysis

- Ambient Conditions → Reference Speed of Sound a_t
- Impeller Tip Speed → Reference Velocity u_2
- Dimensionless Velocity Triangle and Euler Equation

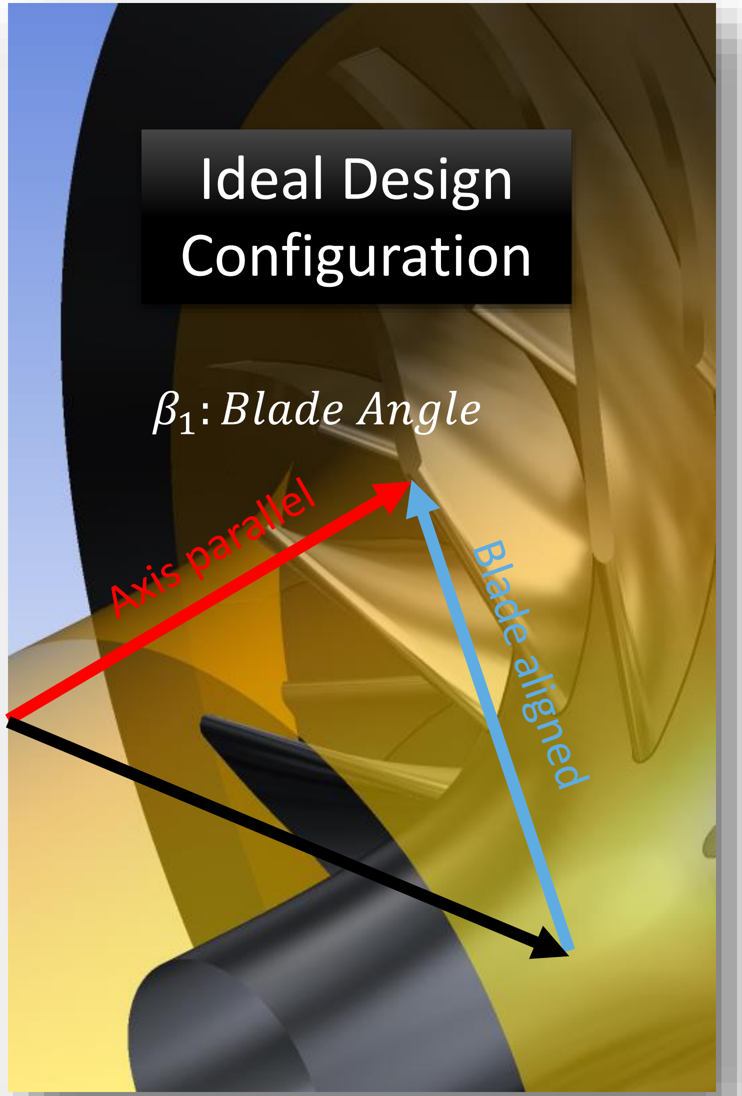
$$\frac{h_{t2}}{h_{t1}} = 1 + (\kappa - 1)\underbrace{\frac{u_2^2}{\kappa R T_{t1}}}_{M_{t,u}^2}\underbrace{\frac{c_u}{u_2}}_{\psi}$$

Dimensionless Velocity Triangle by Ψ, φ and β.
For all: meaningful upper and lower Bounds possible, without Constraint



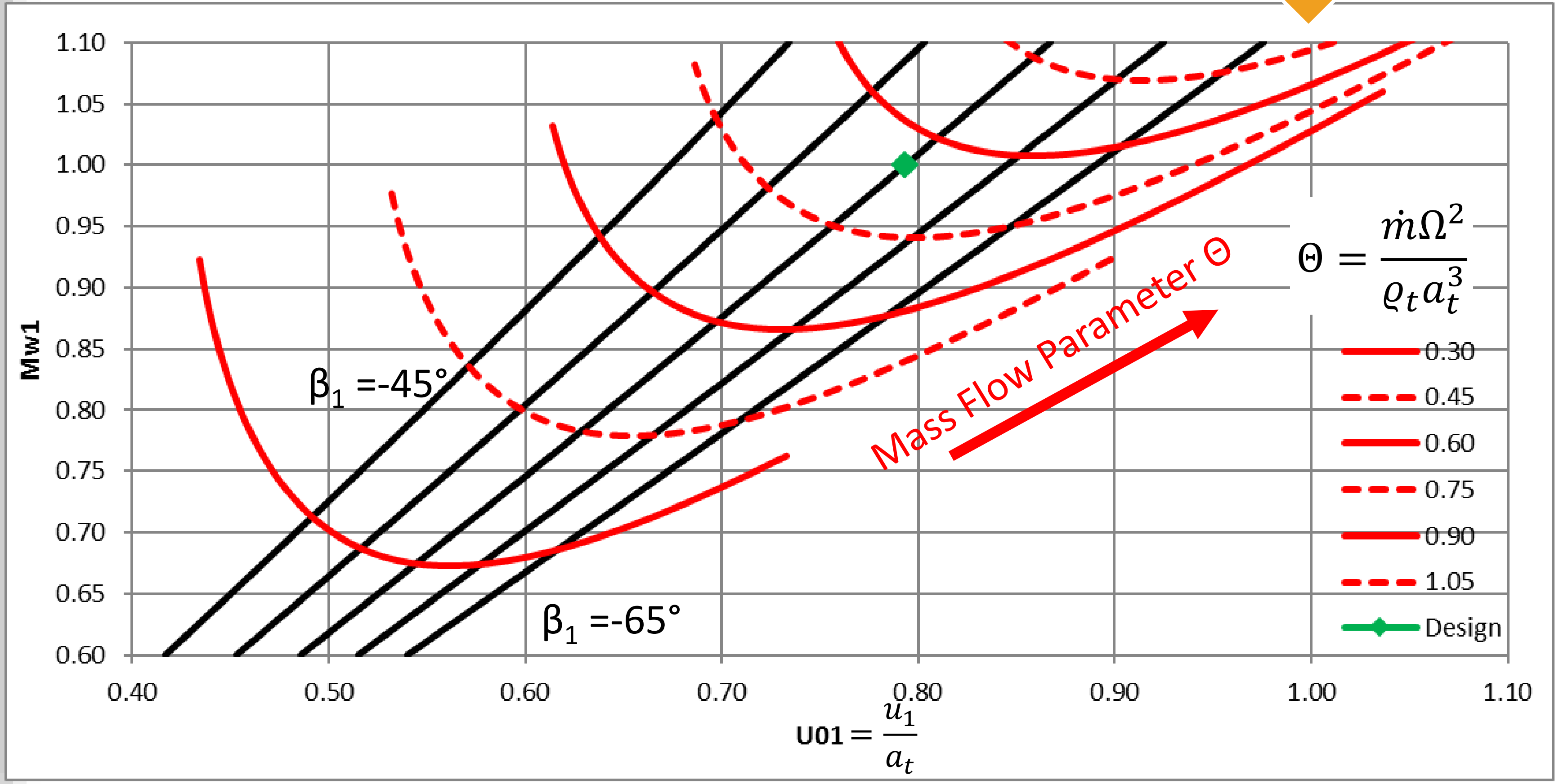


Inducer Design

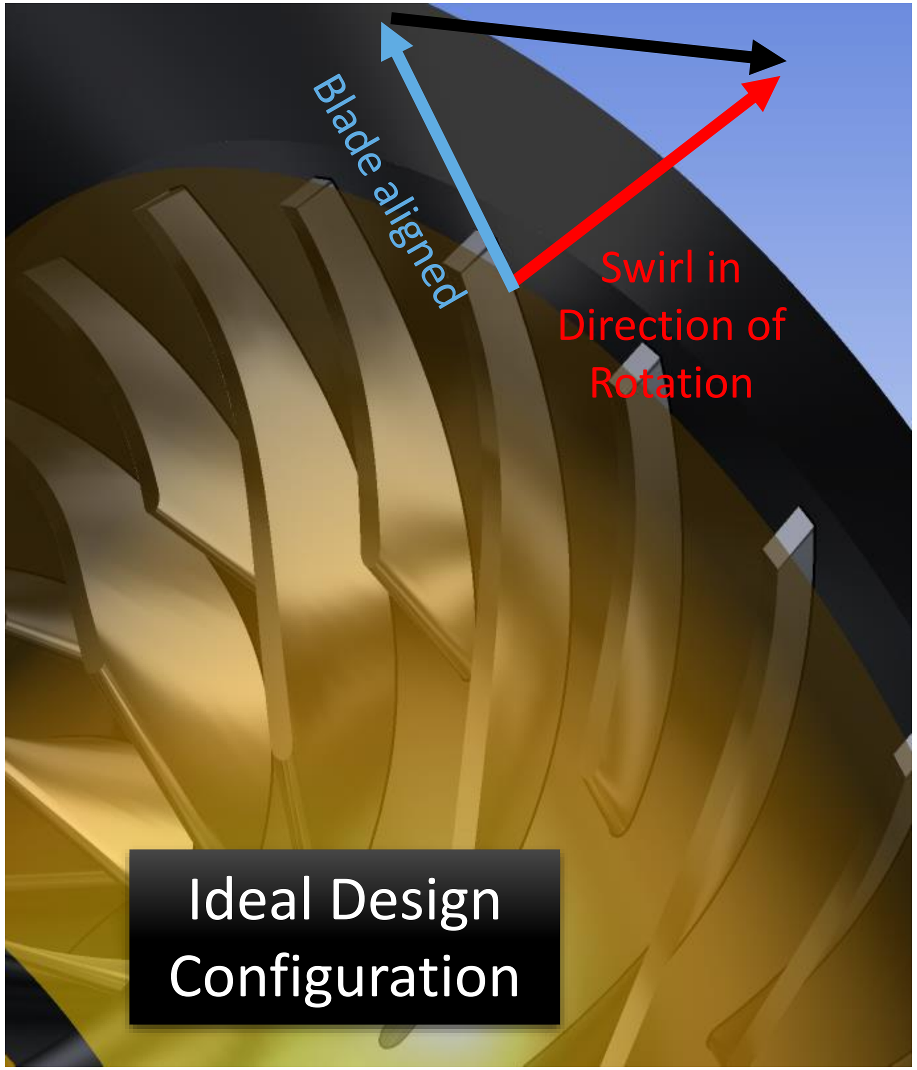


Native Parameters: c_1, w_1, u_1, β_1, r_1, Ω, T_{t1}
Dimensionless: Velocity Triangle + Mass Flow Definition
Design Requirement: low M_{w1} → low Friction

Velocity Triangle + Mass Flow Rate



Discharge Design

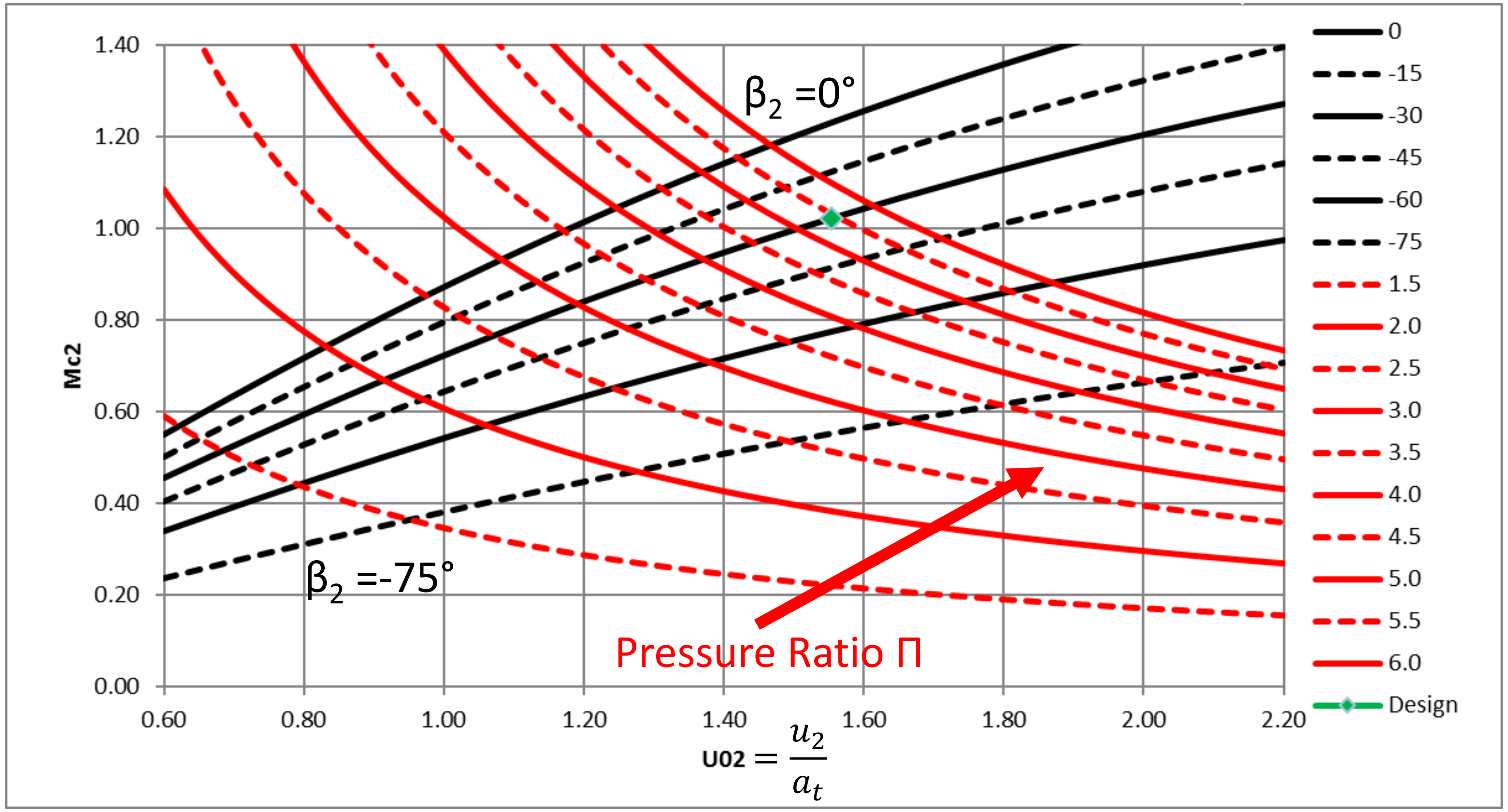


Native Parameters: c_2, w_2, u_2, β_2, r, Ω, T_{t1}, T_{t2}, p_{t1}, p_{t2}

Dimensionless: Velocity Triangle + Euler Equation

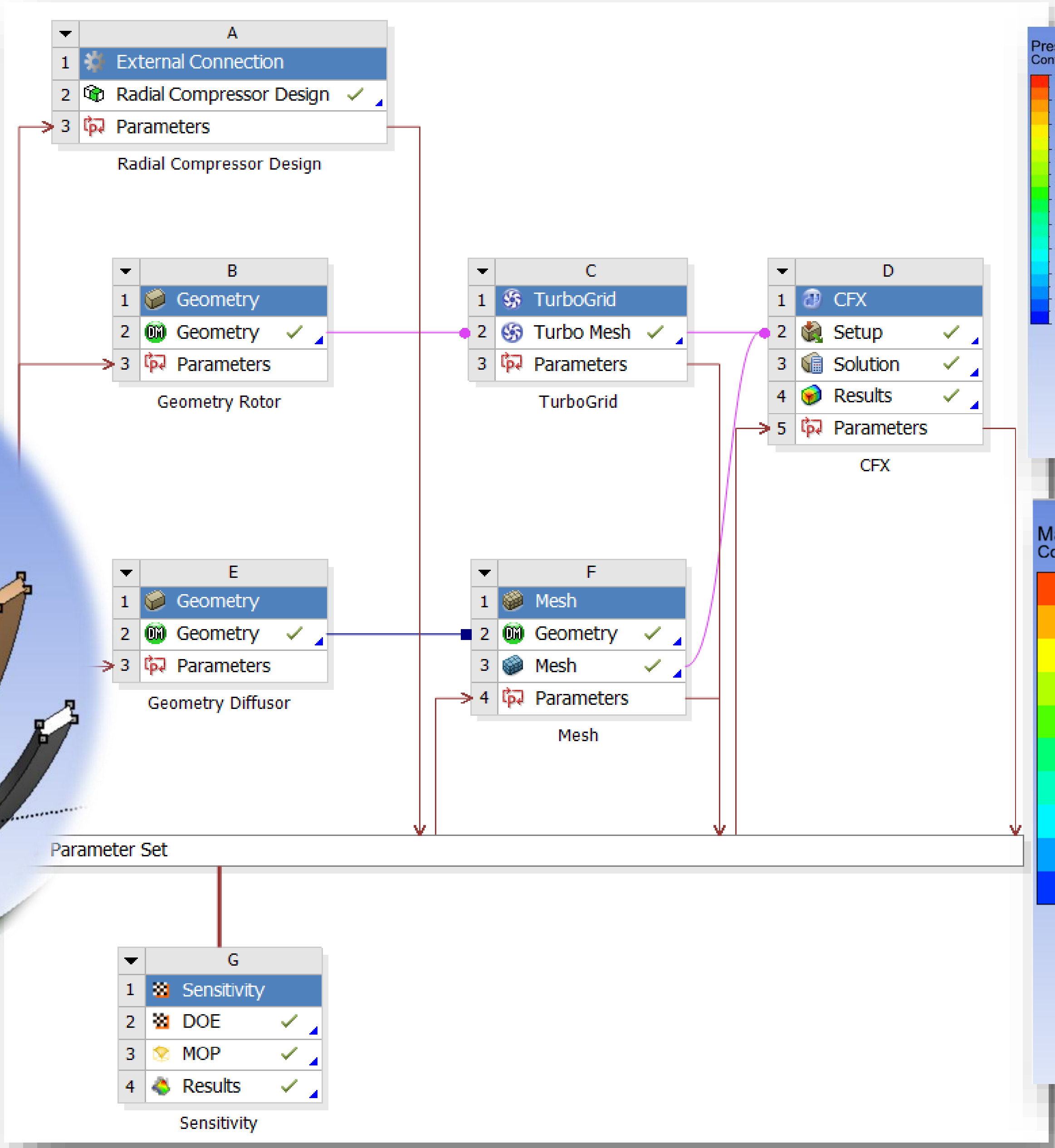
Additional Correlation: $\Pi = f(\Theta, n_s)$

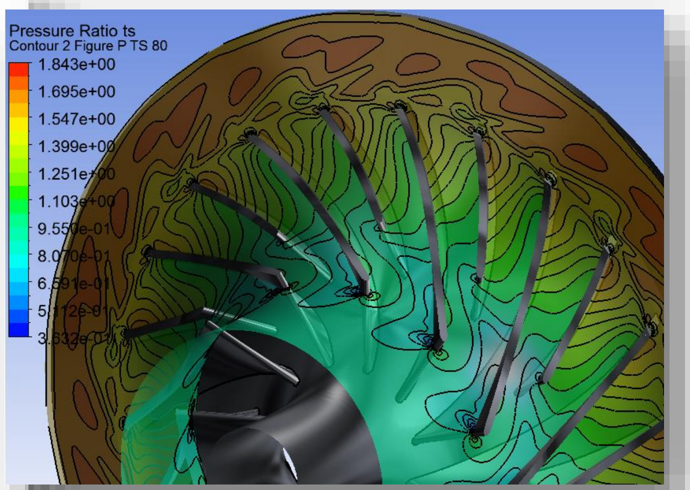
Velocity Triangle
+
Euler Equation

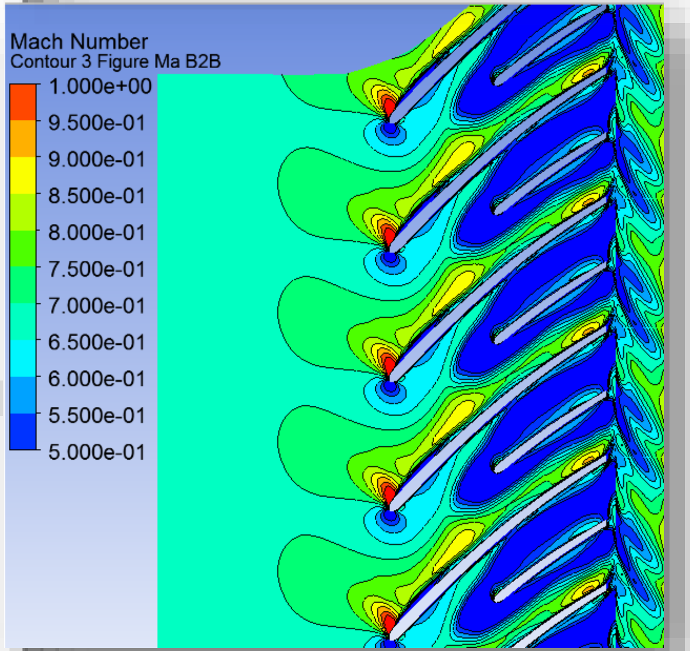


Workflow

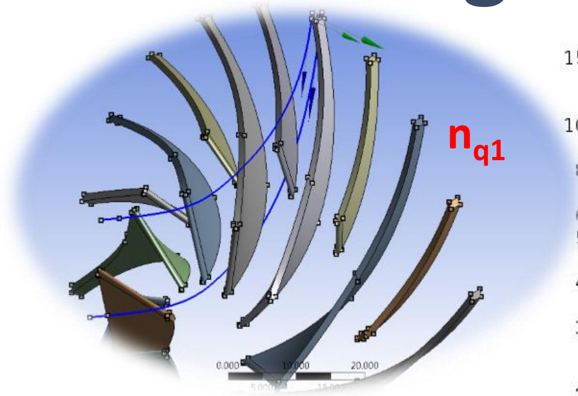
WB-Python Script to compute Main Dimensions wrt to Input Parameter

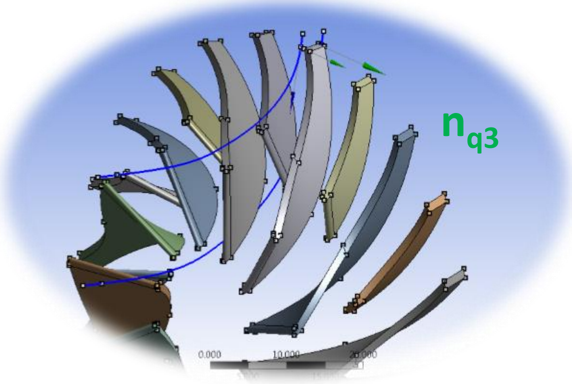


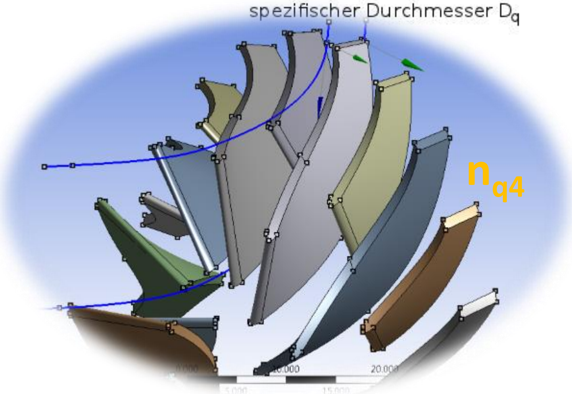


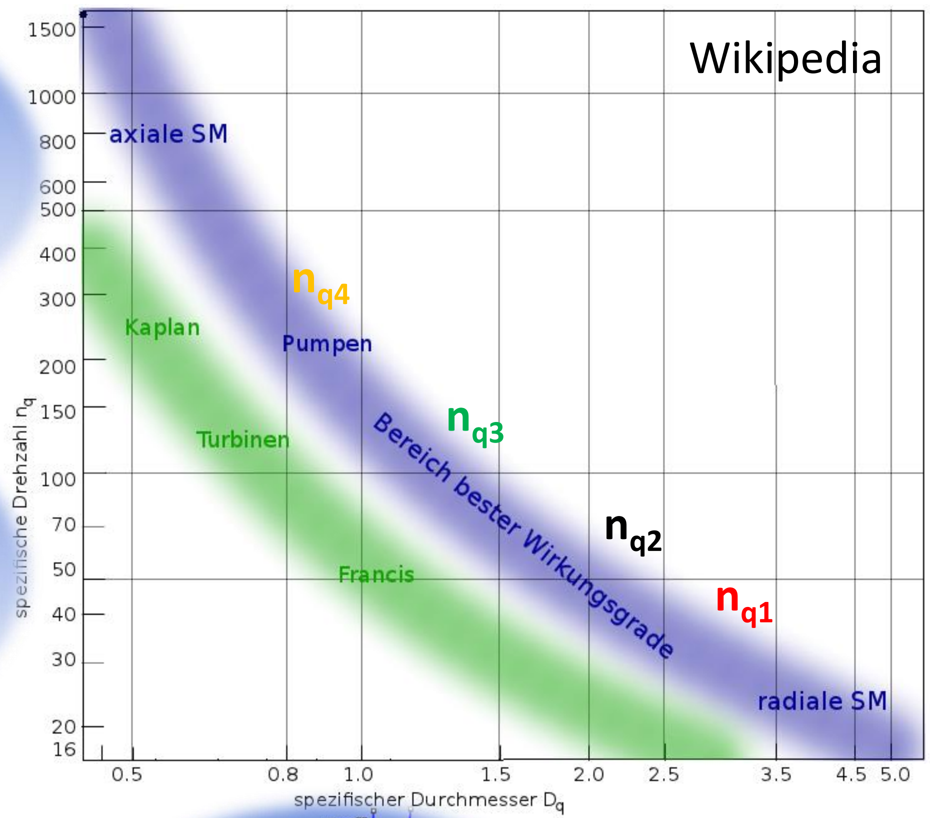


Cordier Diagram

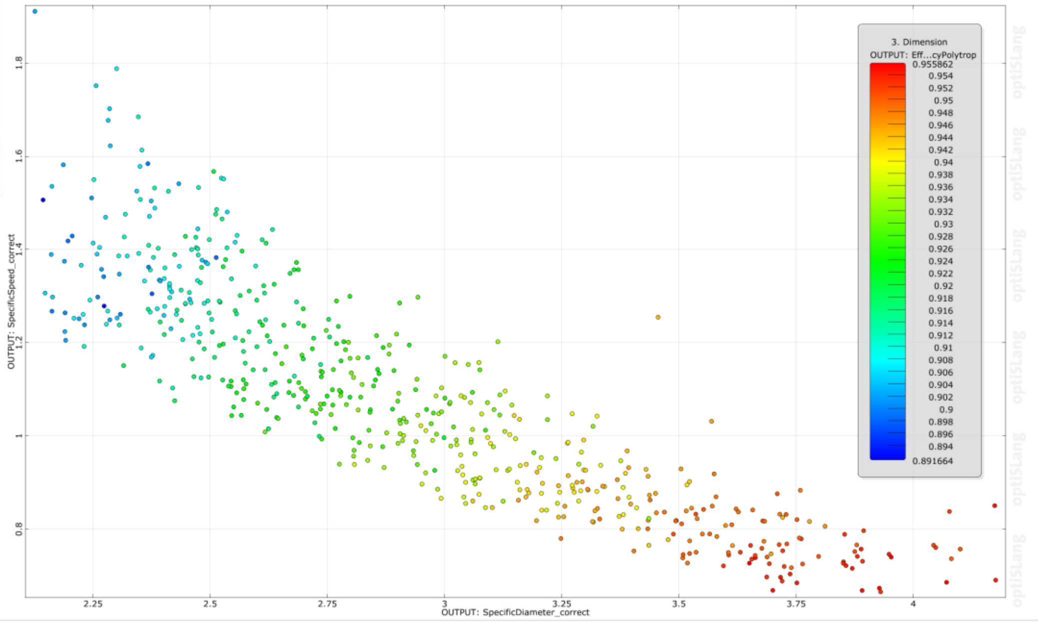






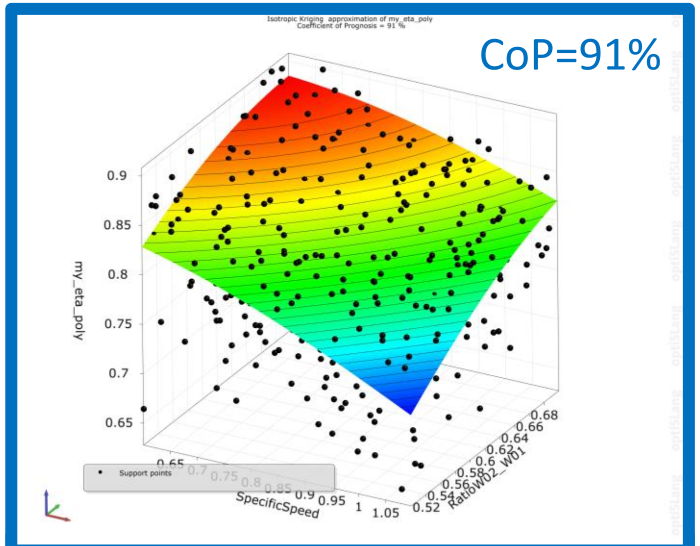


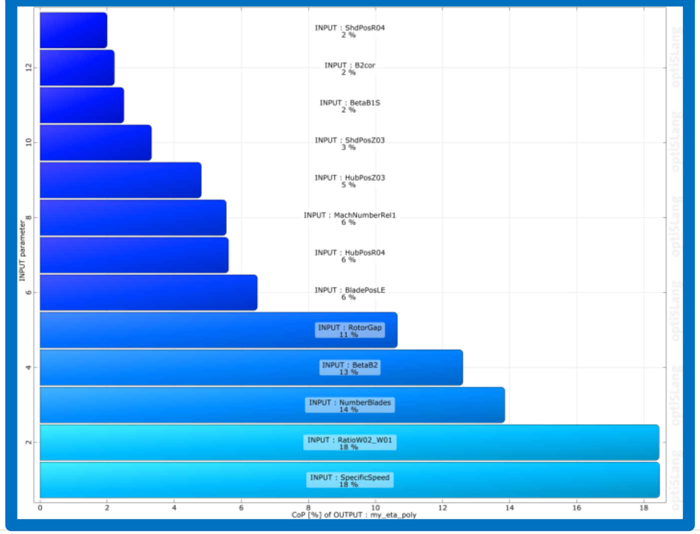
Parameterization respects Cordier Correlation
Polytropic Efficiency in Meta-Model Sampling between 89.1% and 95.5%

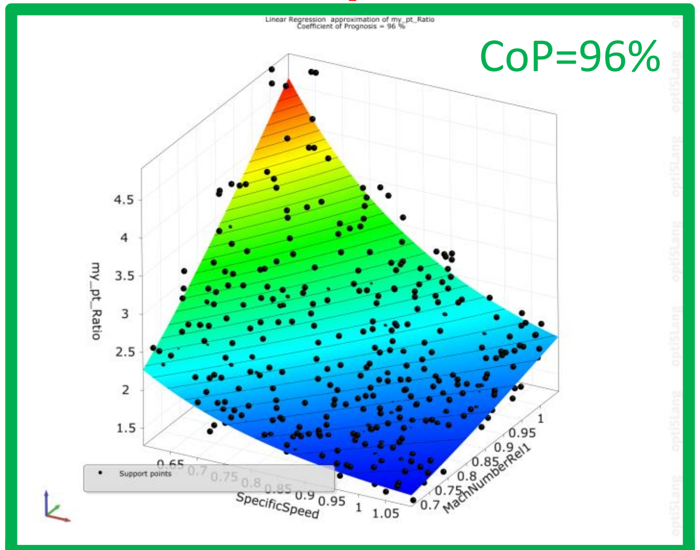


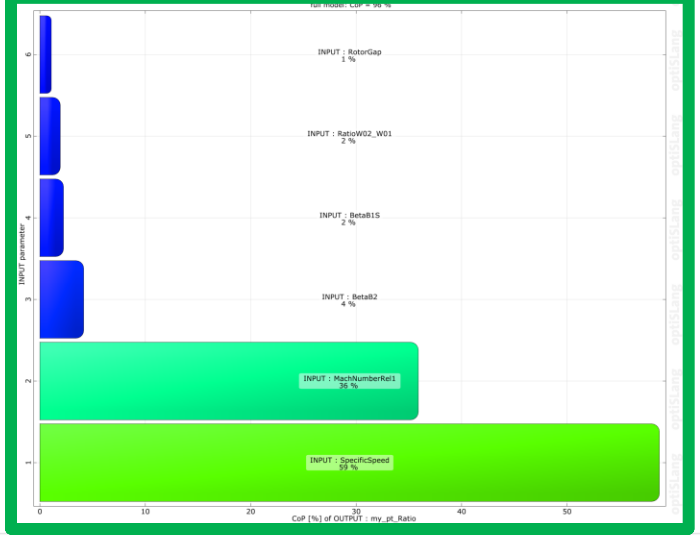
Result – State Variables

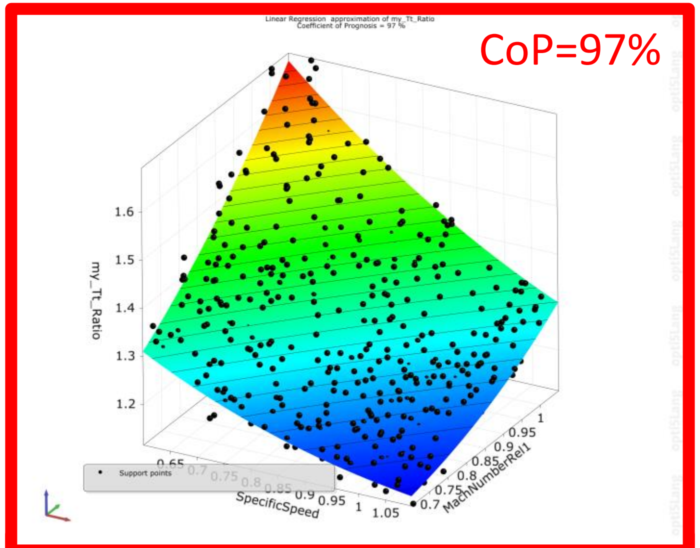
$$Polytropic\ Efficiency = \frac{\kappa - 1}{\kappa} \frac{\ln(Total\ Pressure\ Ratio)}{\ln(Total\ Temperature\ Ratio)}$$



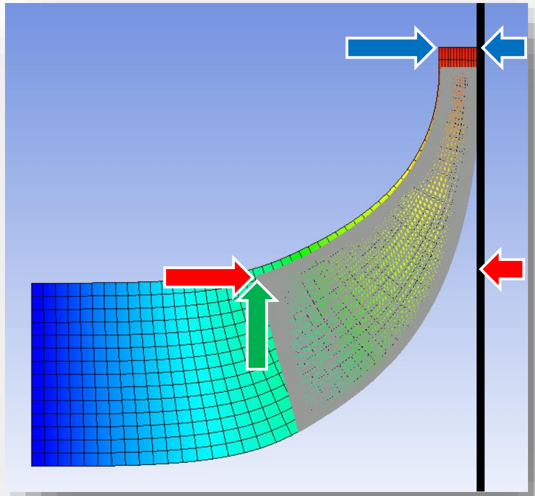




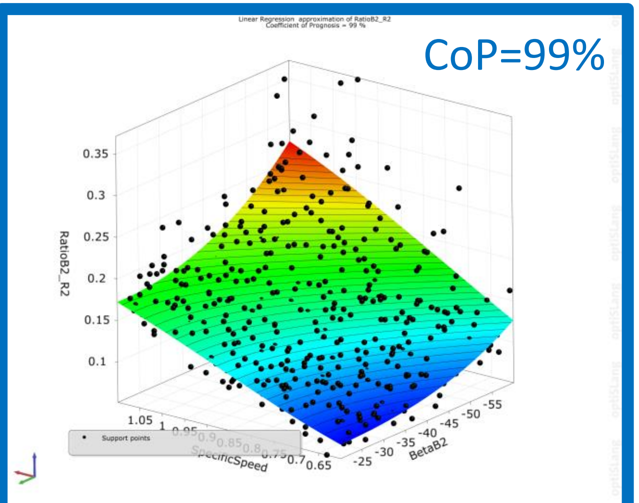


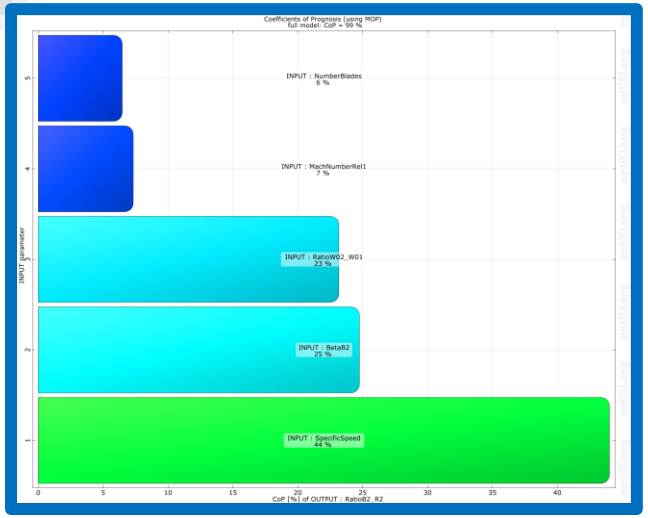


Results – Design Correlations

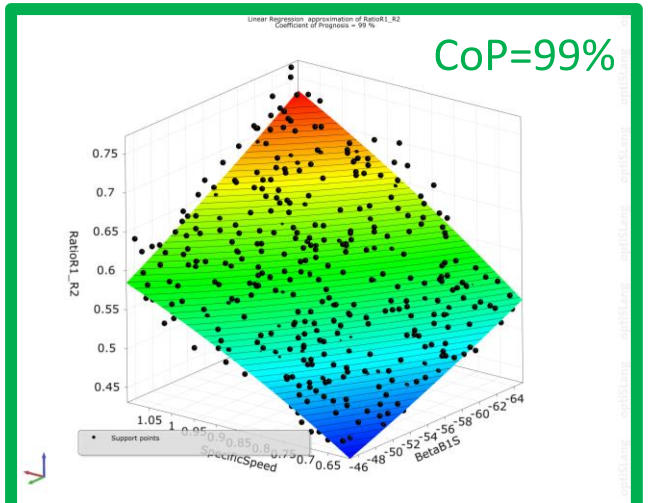


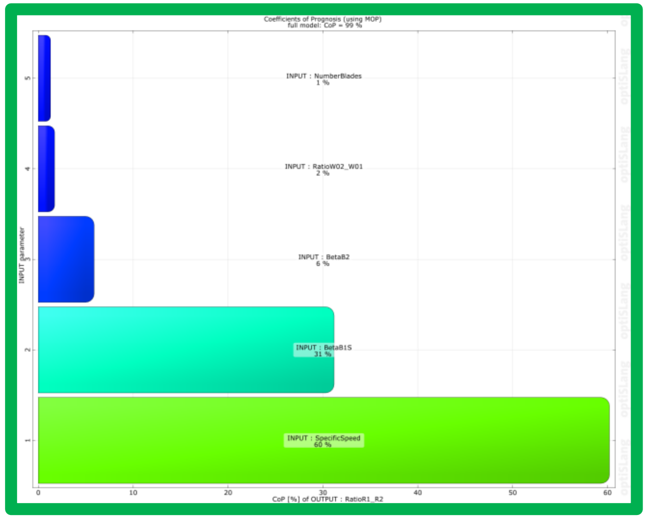
Channel Hight b_2/r_2



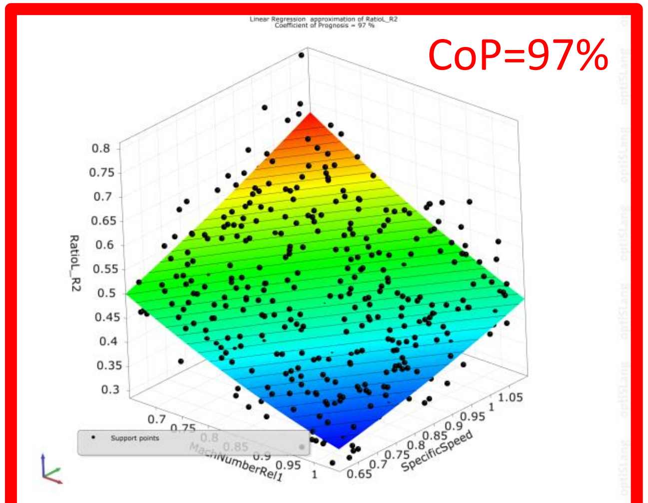


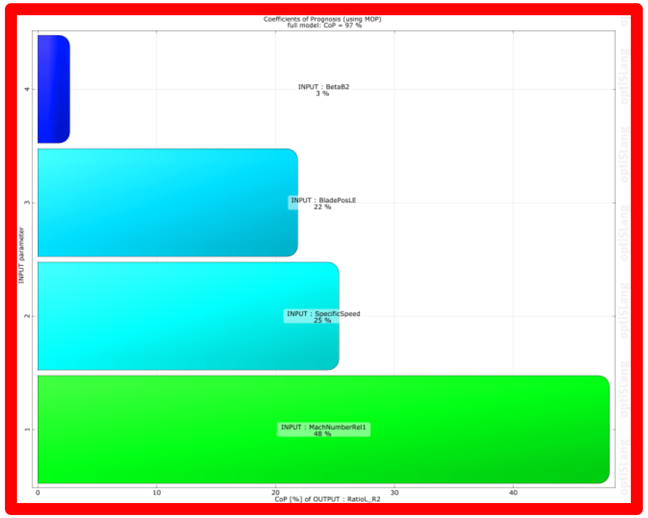
Inducer Radius r_1/r_2





Blade Length L/r_2

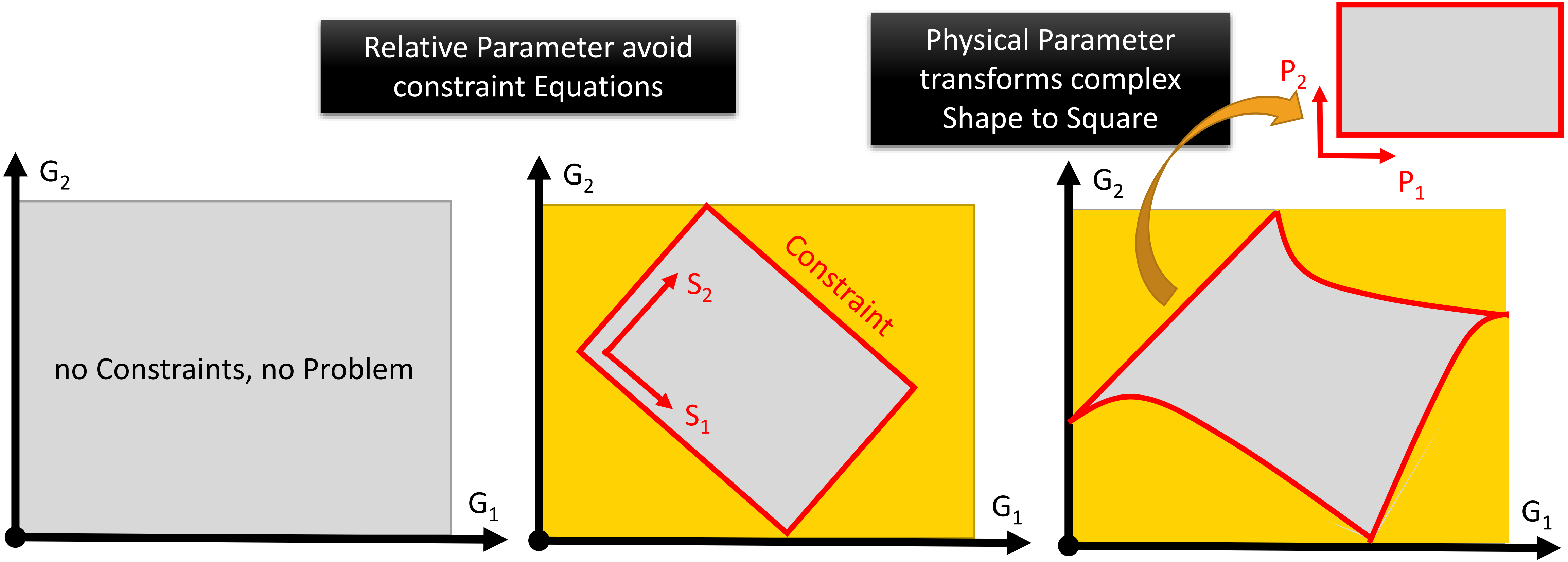




Usefull Infomration for further primary Design

Summary – Parametrization

- Geometry Parameters G_i are very easy to define and vary
- Geometric and/or Physical Constraints might be needed → Use Relative Parameters S_i
- Geometric and/or Physical Constraints can become complex → Use Relative Parameters P_i



Key to Successful Optimization