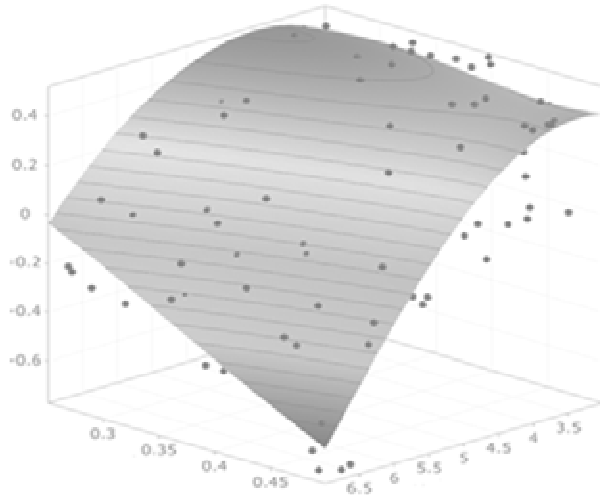
Relevance of Modern Optimization Methods in Turbo Machinery Applications

- From Analytical Models via Three Dimensional Multidisciplinary Approaches to the Optimization of a Wind Turbine -



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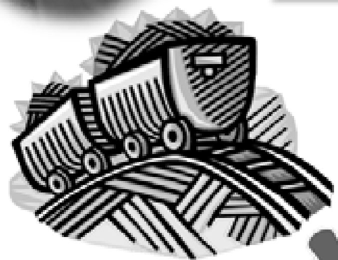
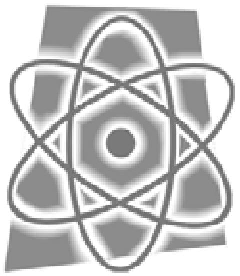
Presented by the Research Center

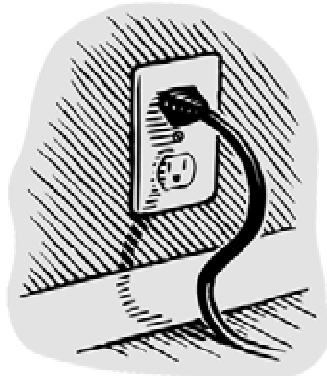
„Computer Simulation in Mechanical Engineering“

Partner of the

InnovationsAllianz
DER NRW-HOCHSCHULEN E.V.







In nearly every case turbomachinery is an essential component for energy conversion.

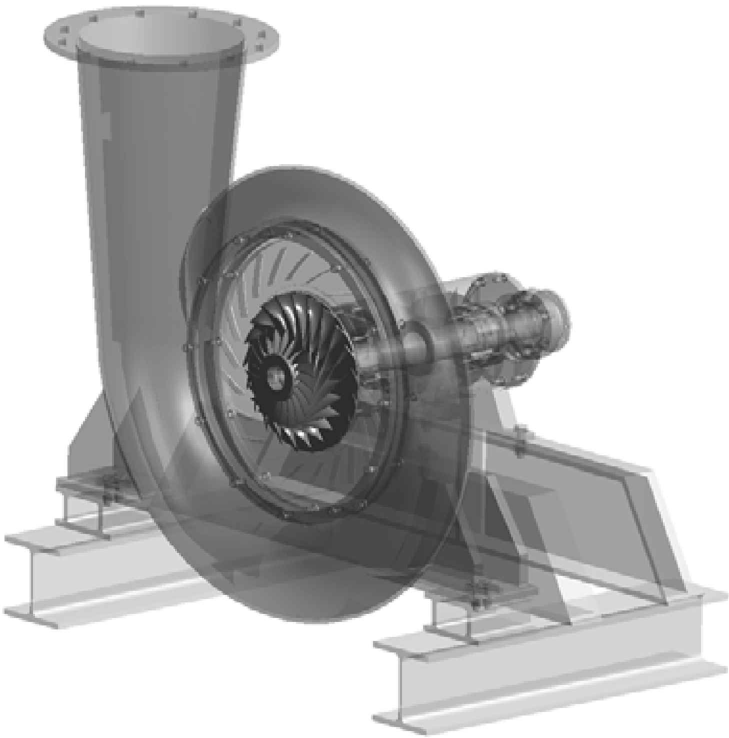
Motivation

- Important component for energy conversion
- Energy efficiency is a global problem
- Complex physical phenomena
- High computational expense

→ **Efficient optimization strategies are essential!**

CONTENTS

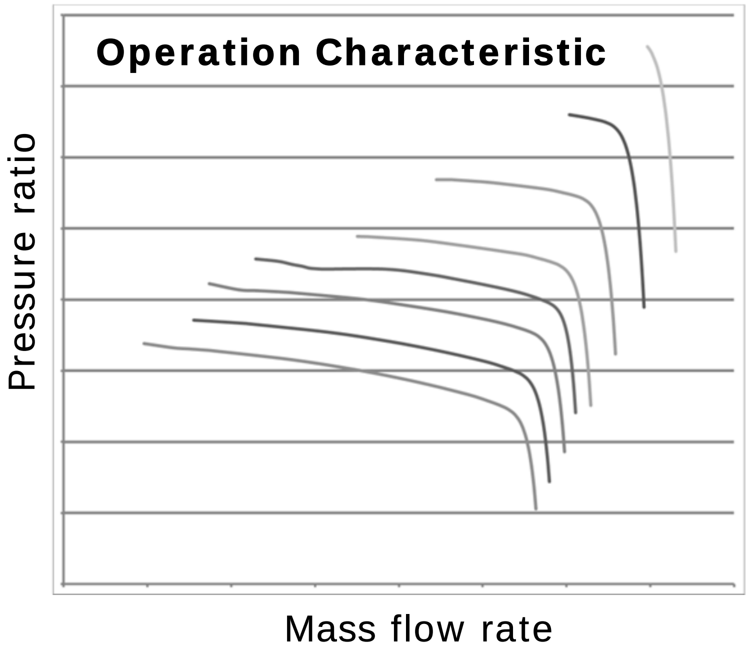
One Dimensional Radial Impeller Optimization



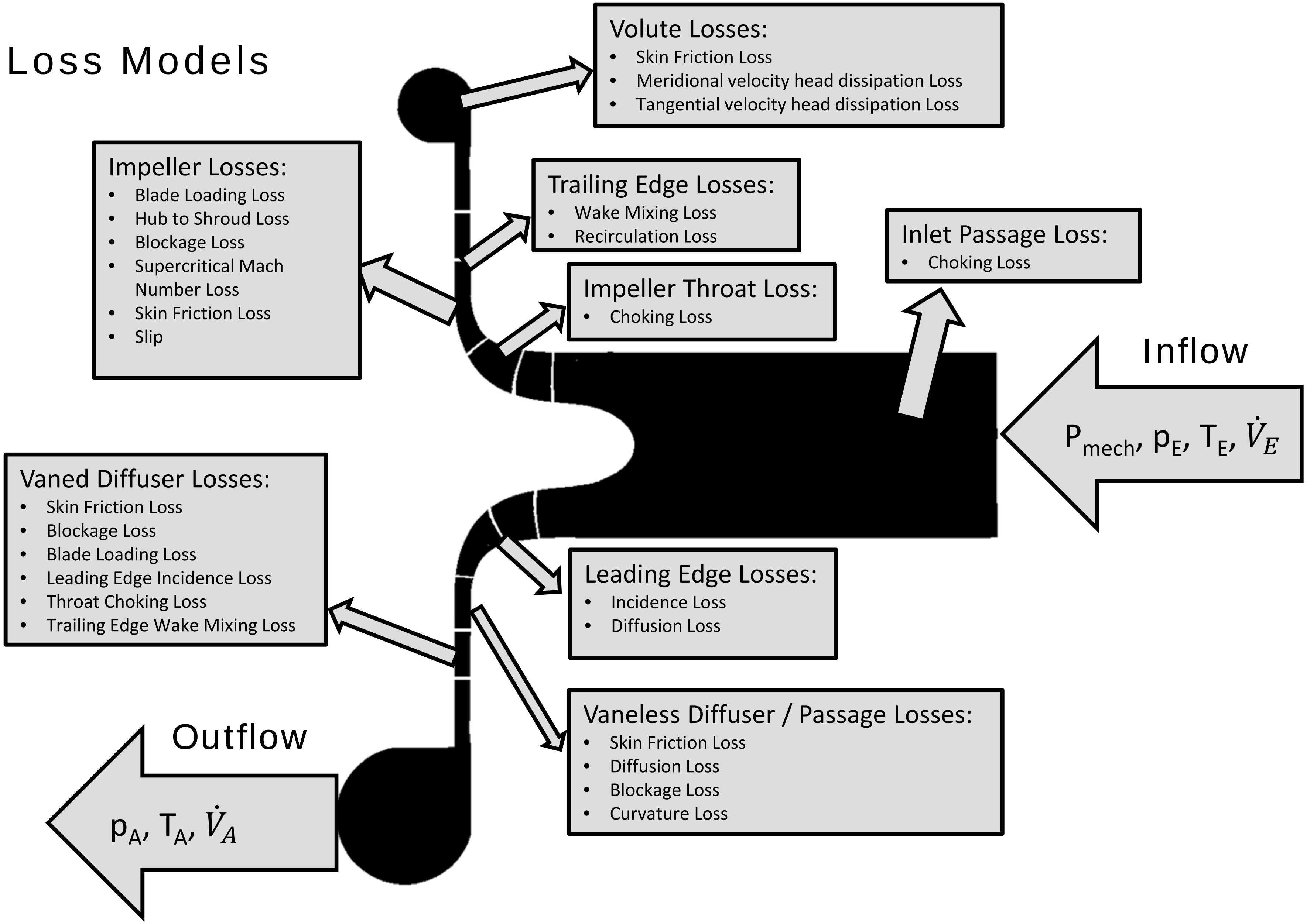
Goal:

Prediction of the operation characteristic of a single stage radial compressor with loss modells for every machine component.

Results:



Loss Models

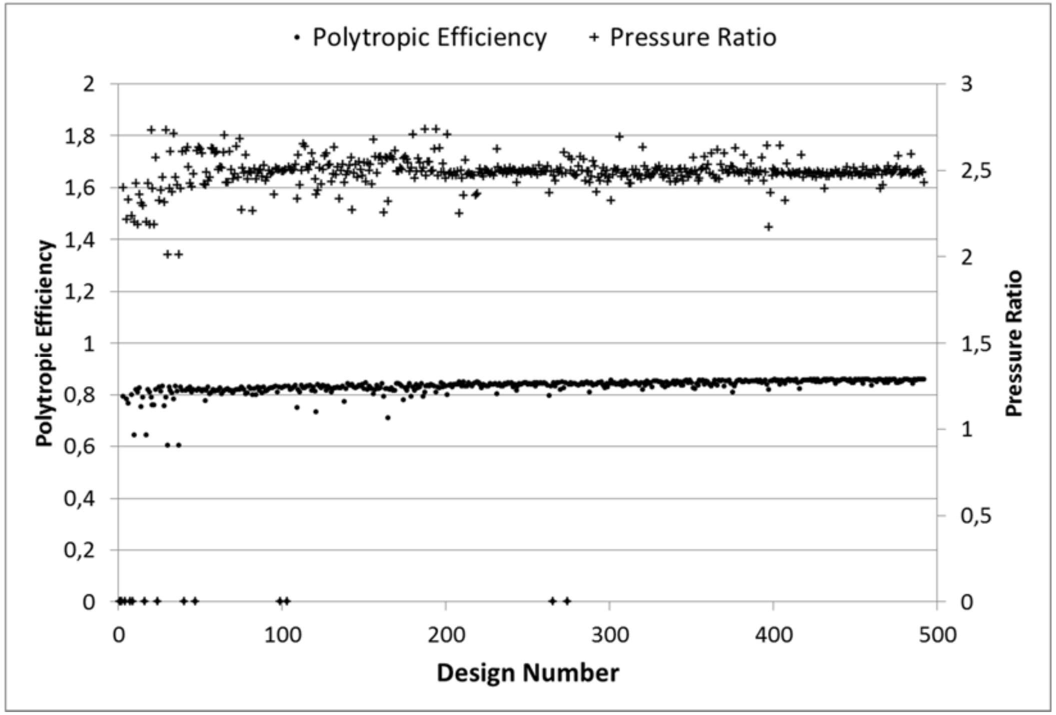

Volute Losses:
• Skin Friction Loss
• Meridional velocity head dissipation Loss
• Tangential velocity head dissipation Loss
Impeller Losses:
• Blade Loading Loss
• Hub to Shroud Loss
• Blockage Loss
• Supercritical Mach Number Loss
• Skin Friction Loss
• Slip
Trailing Edge Losses:
• Wake Mixing Loss
• Recirculation Loss
Inlet Passage Loss:
• Choking Loss
Impeller Throat Loss:
• Choking Loss
Inflow
P_{mech}, p_E, T_E, $\dot{V}_E$
Vaned Diffuser Losses:
• Skin Friction Loss
• Blockage Loss
• Blade Loading Loss
• Leading Edge Incidence Loss
• Throat Choking Loss
• Trailing Edge Wake Mixing Loss
Leading Edge Losses:
• Incidence Loss
• Diffusion Loss
Vaneless Diffuser / Passage Losses:
• Skin Friction Loss
• Diffusion Loss
• Blockage Loss
• Curvature Loss
Outflow
p_A, T_A, $\dot{V}_A$

Optimization

14 input parameters

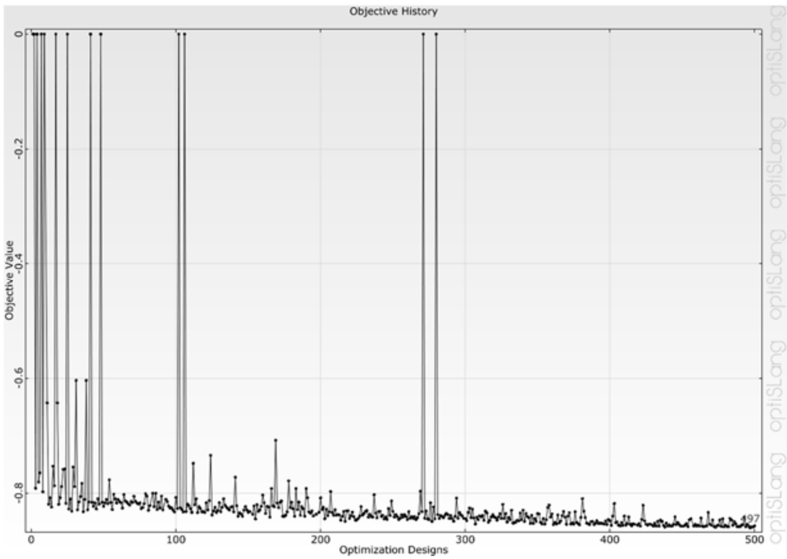
Fast calculation: less then one minute per design point

→ A direct optimization with an evolutionary algorithm can be used!



Results

Optimization



Design of an optimal stage with
N = 21120 rev/min
Impeller diameter = 340 mm
Pressure ratio > 2

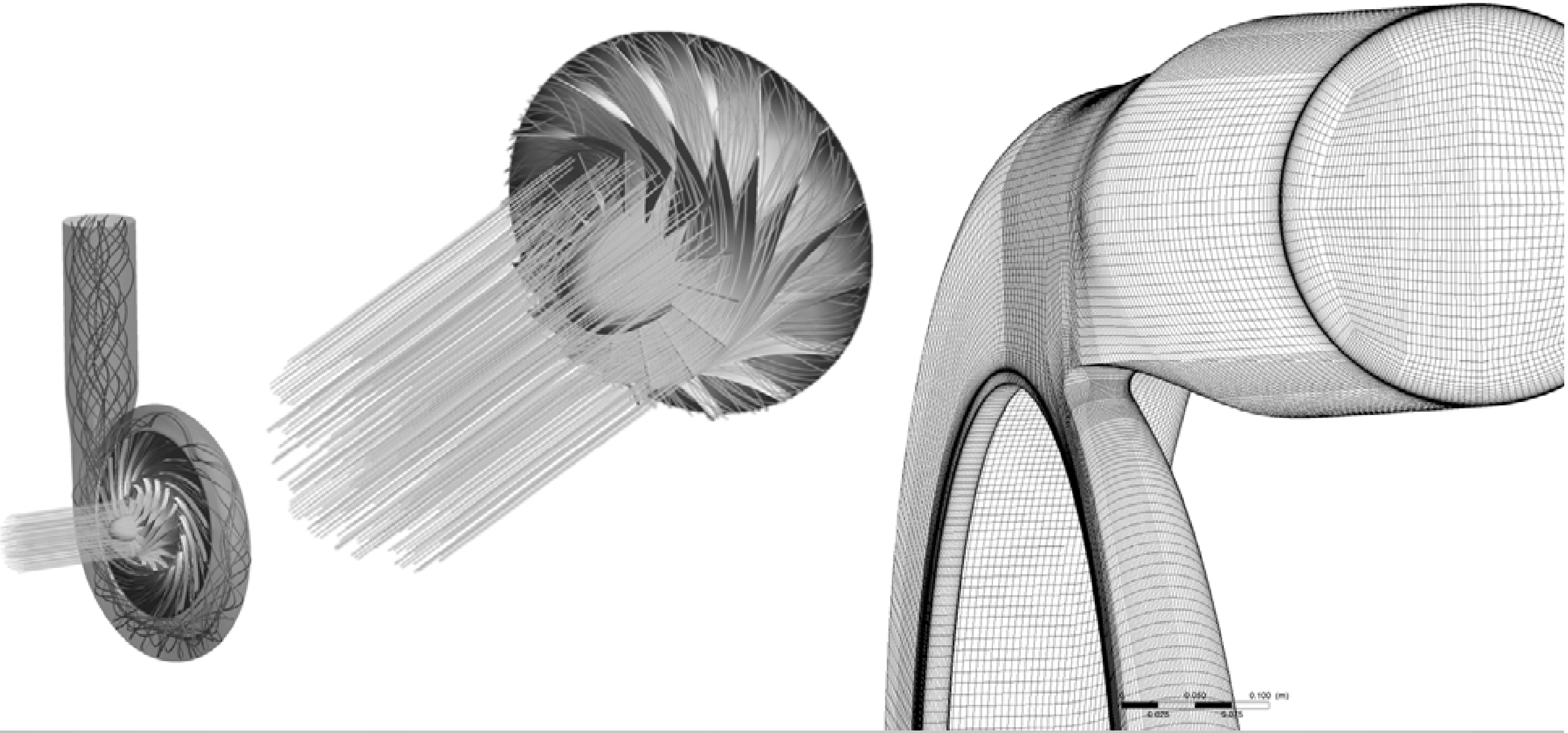
Due to numerical instabilities at stall and choke operation a single point optimization at operation condition is preformed.

	Start Design	Optimal Design
Pressure Ratio	2.40	2.47
Efficiency	**79%**	**85%**

A rise of 6 points in efficiency can be obtained by a fast method!

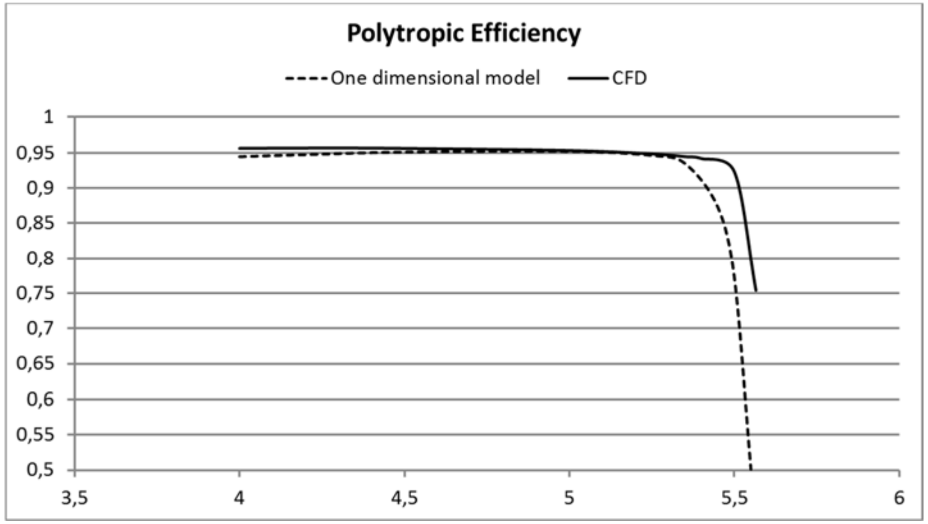
Results

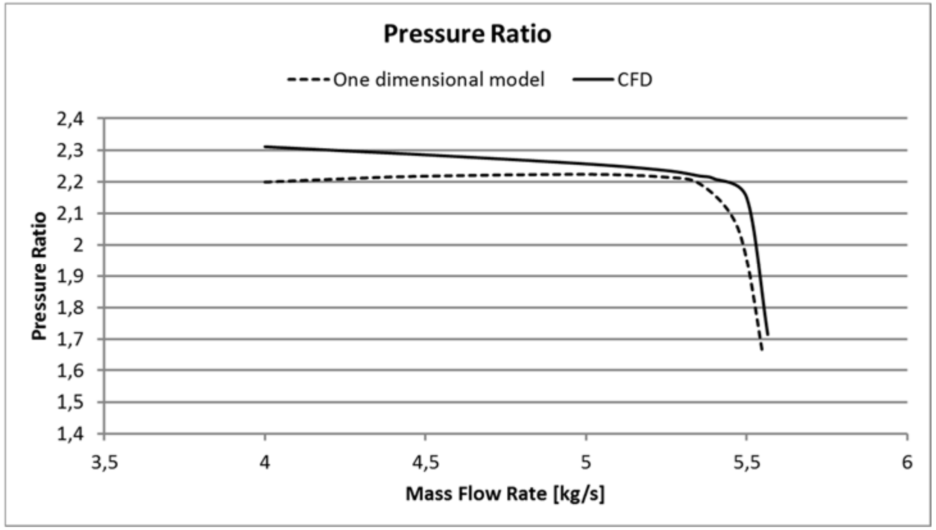
CFD Validation
(Complete Stage, ~25 Mill. Elements, High Fidelity CFD)



Results

Comparison of one dimensional and CFD compressor characteristic





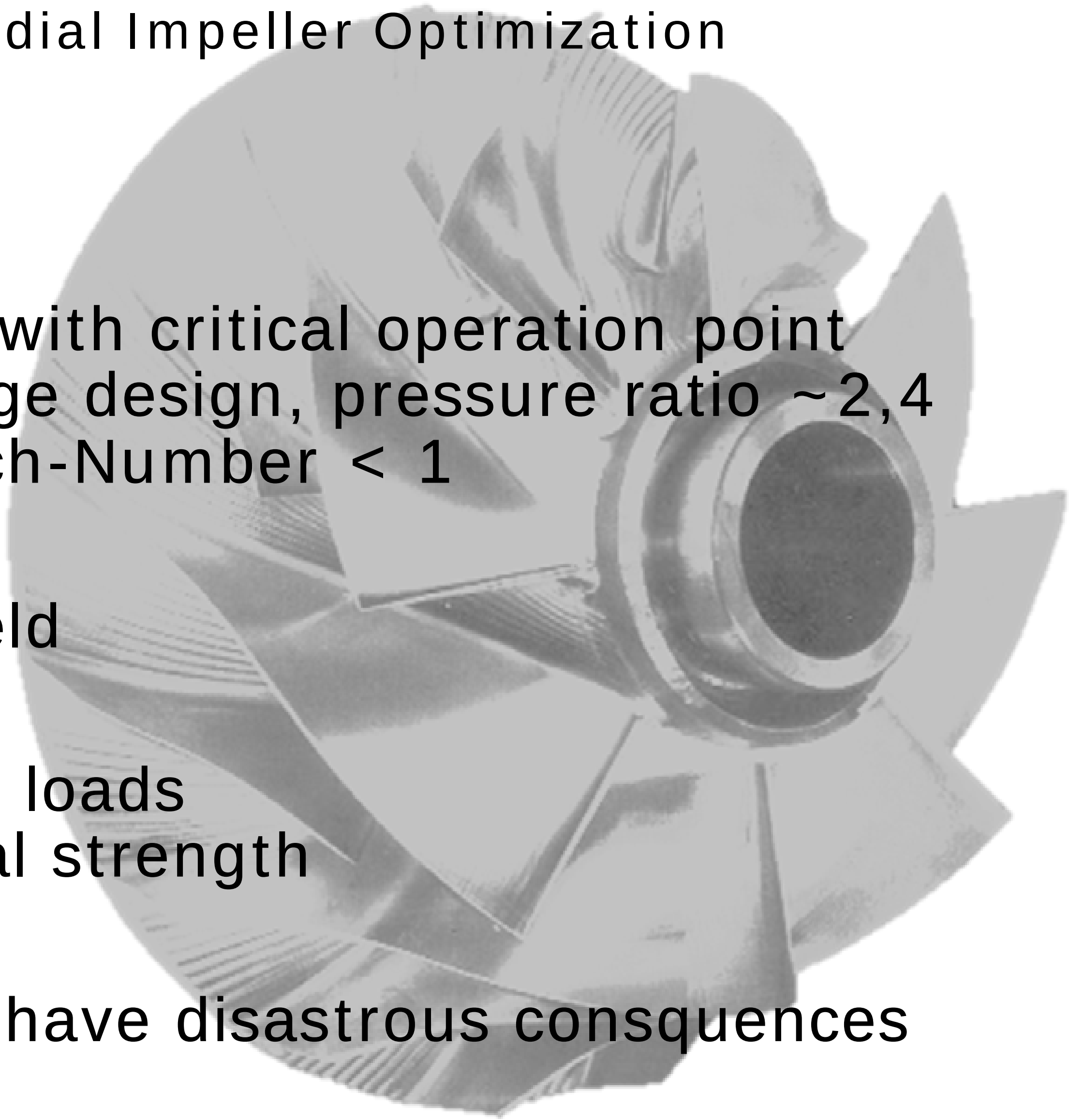
The one dimensional and the CFD model show good correlation.

Contents

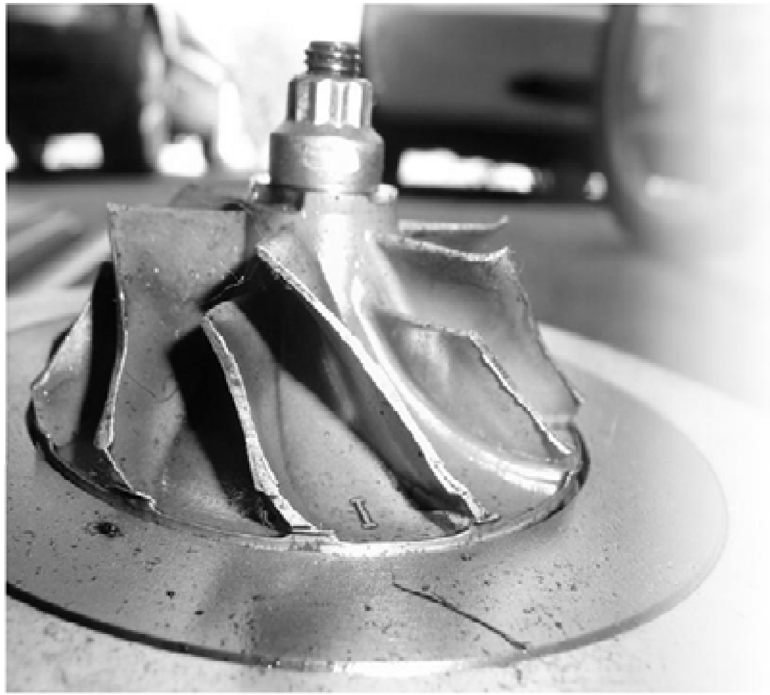
Three Dimensional Radial Impeller Optimization

Challenges:

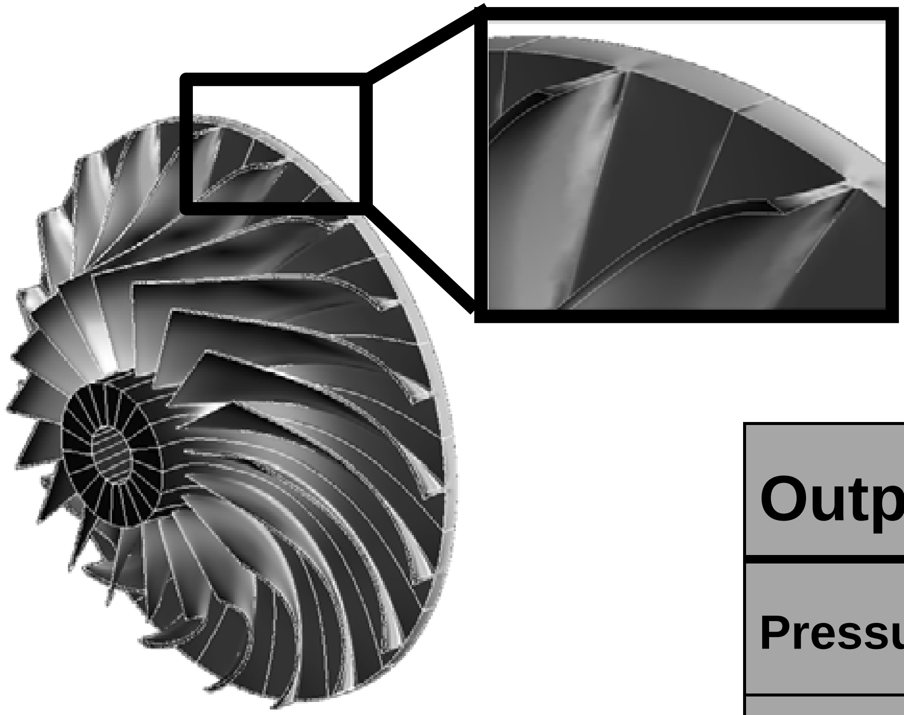
- Impeller design with critical operation point
  → single stage design, pressure ratio ~2,4
  → 0,9 < Mach-Number < 1
- Complex flow field
- High mechanical loads
  → Machanical strength
- Errors in design have disastrous consquences



Examples for Impeller Damage



Startdesign with N = 20.000 rev/min



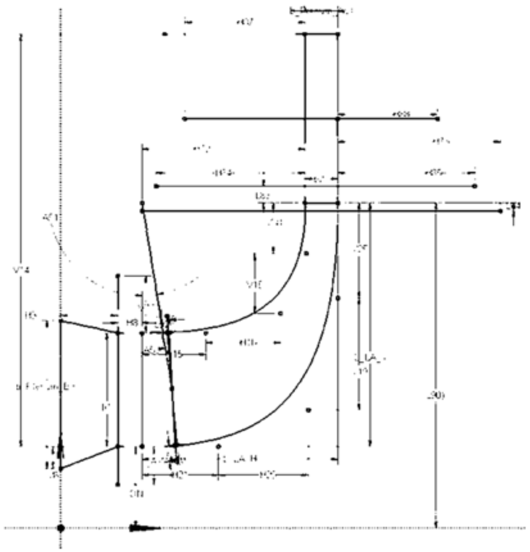
Startdesign generated with
1D – design tool
(pure fluid mechanic design)

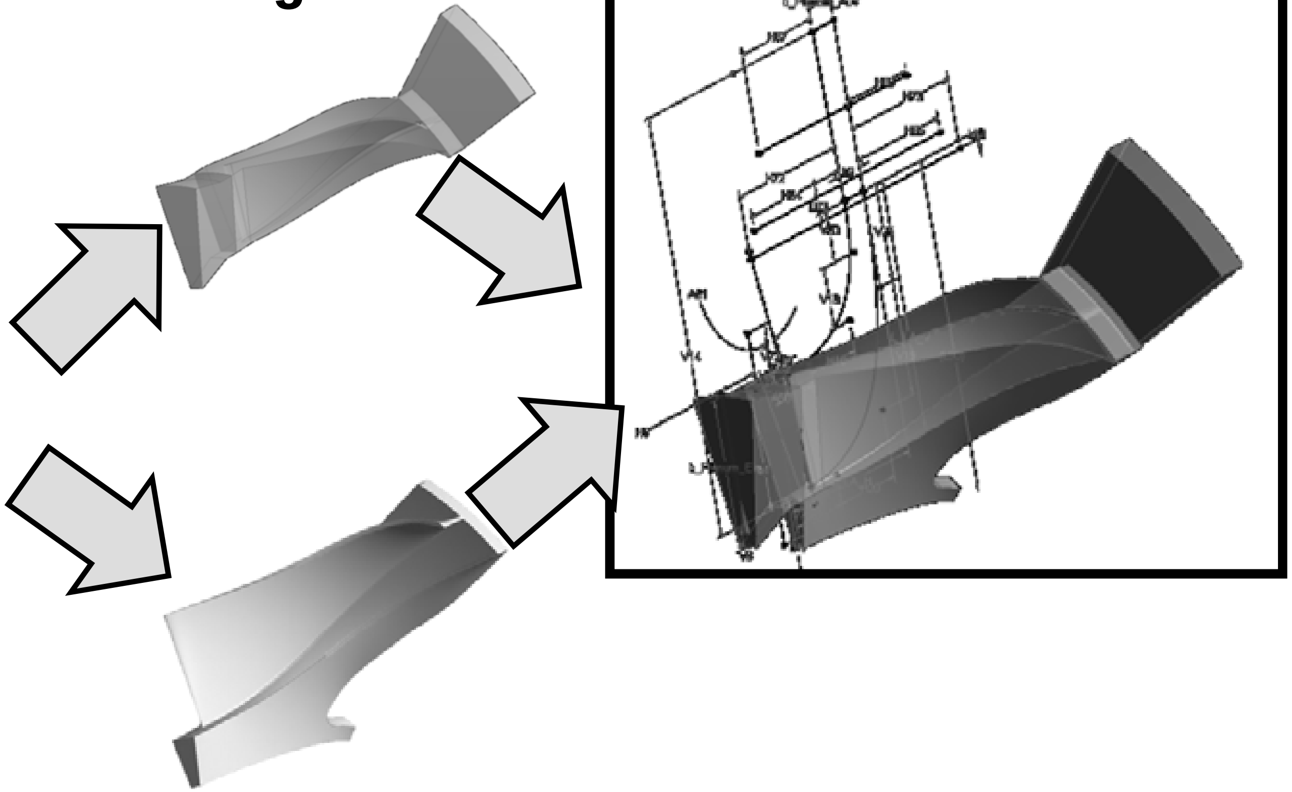
Output	Value
Pressure Ratio	$\Pi = 2.4$
Polytrophic Efficiency	$\eta_{pol} = 87\%$
Maximum Equivalent Stress	$\sigma_V >> \sigma_{zul}$

Optimization goal:
Lower the stress while retaining the good aerodynamic behaviour!

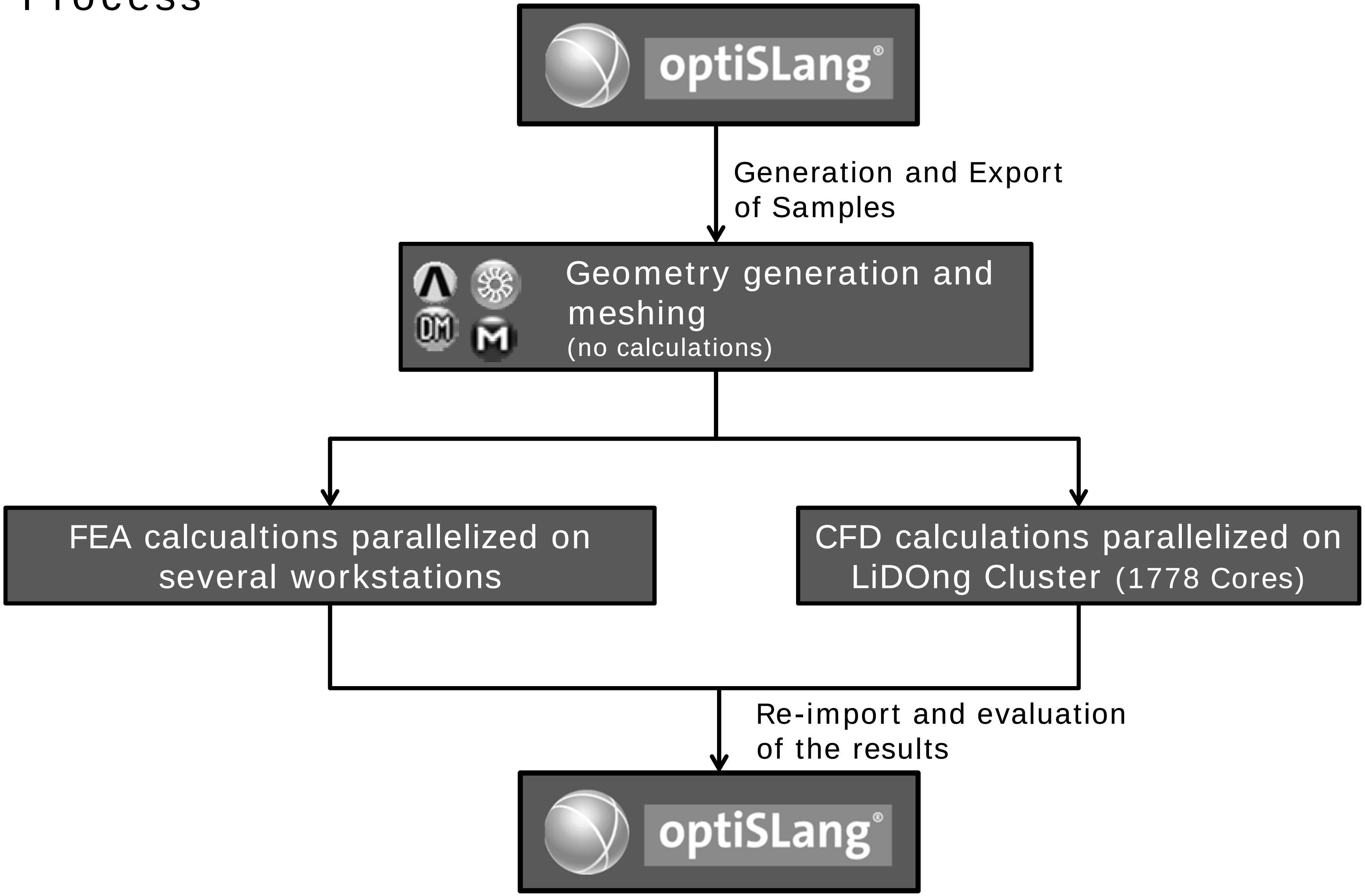
Model

- Robust geometry definition
- Solid geometry based on fluid geometry
- 29 geometric parameters
- → **Arbitrary impeller designs can be modeled!**

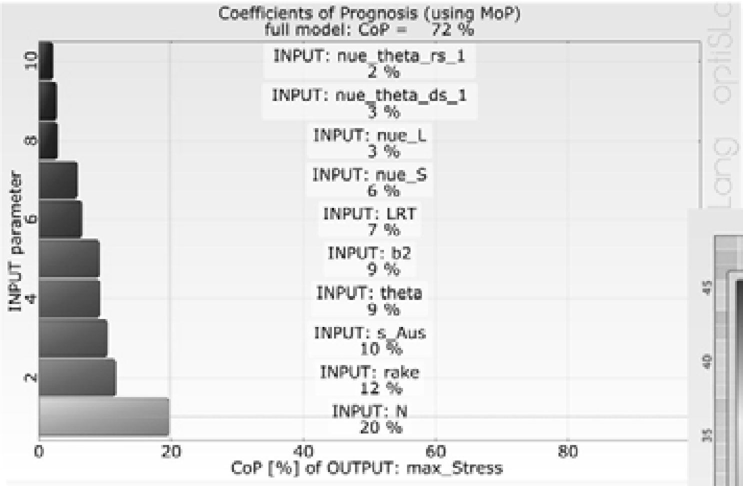


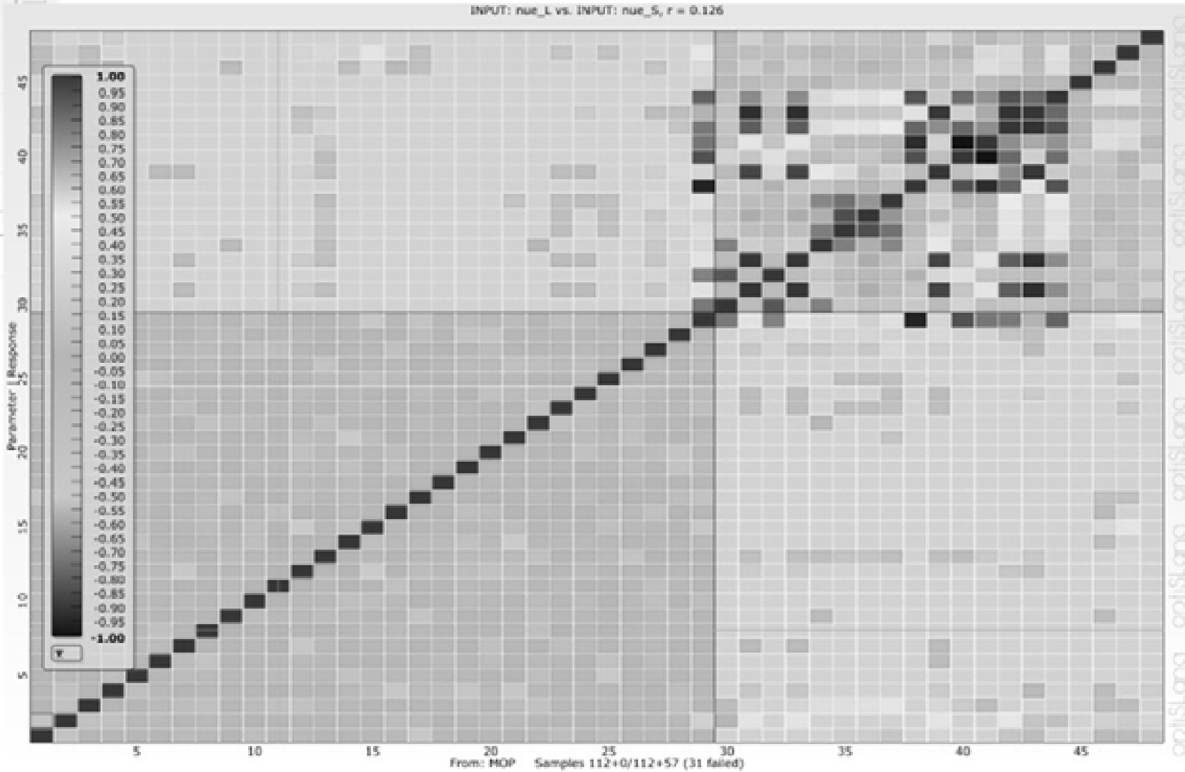


Process


optiSLang®
Generation and Export
of Samples
Geometry generation and
meshing
(no calculations)
FEA calcualtions parallelized on
several workstations
CFD calculations parallelized on
LiDOng Cluster (1778 Cores)
Re-import and evaluation
of the results
optiSLang®

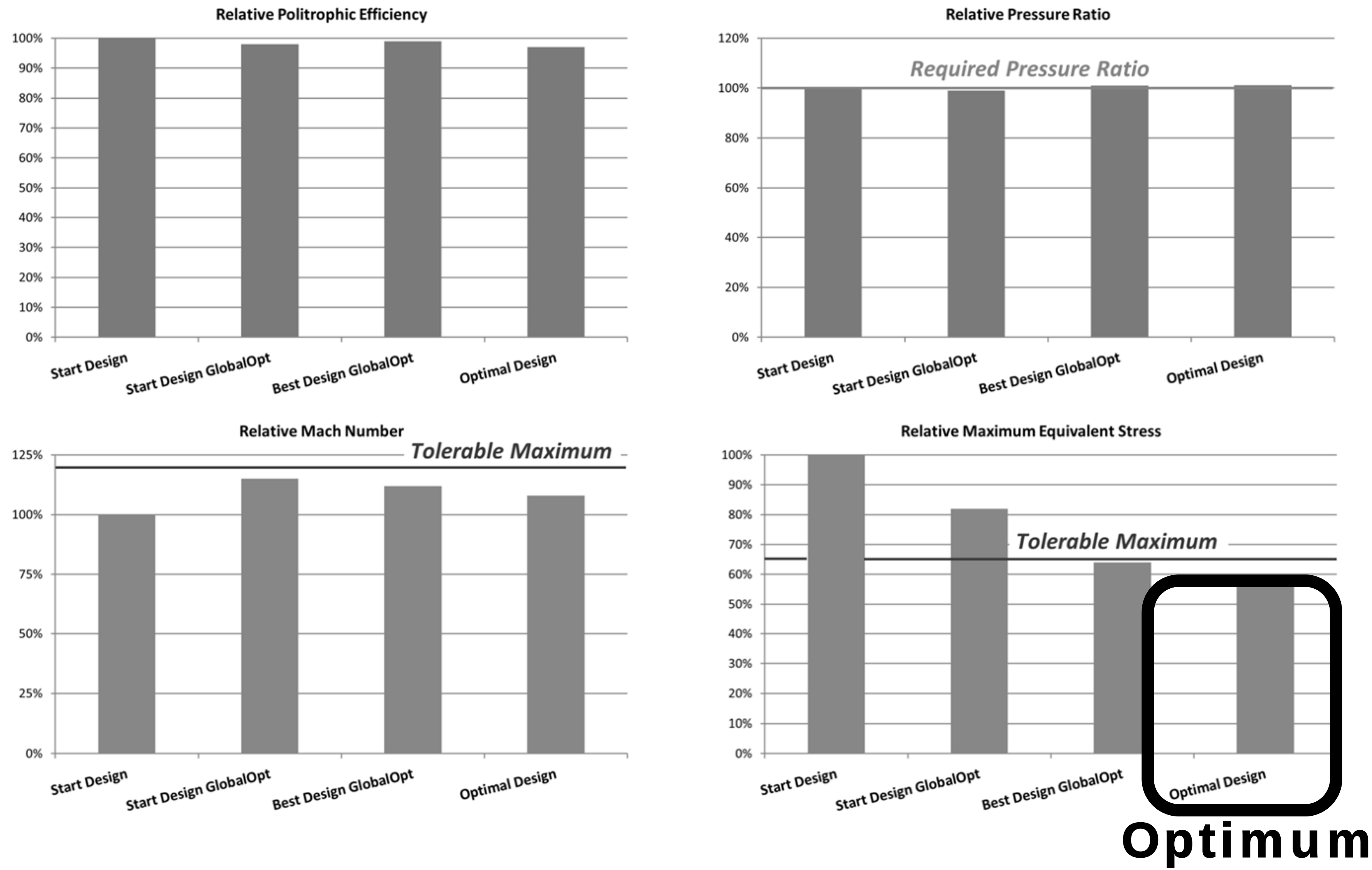
Sensitivity





Reduction of input parameters from 29 to 14!

Results


Relative Politrophic Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Start Design
Start Design GlobalOpt
Best Design GlobalOpt
Optimal Design
Relative Pressure Ratio
Required Pressure Ratio
120%
100%
80%
60%
40%
20%
0%
Start Design
Start Design GlobalOpt
Best Design GlobalOpt
Optimal Design
Relative Mach Number
Tolerable Maximum
125%
100%
75%
50%
25%
0%
Start Design
Start Design GlobalOpt
Best Design GlobalOpt
Optimal Design
Relative Maximum Equivalent Stress
Tolerable Maximum
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Start Design
Start Design GlobalOpt
Best Design GlobalOpt
Optimal Design
Optimum

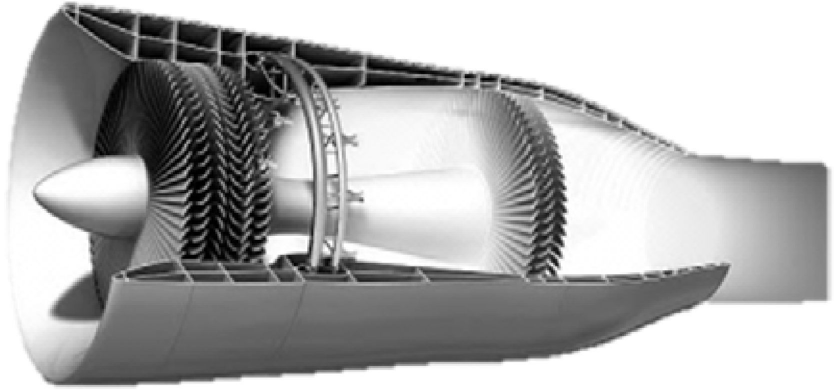
Summary

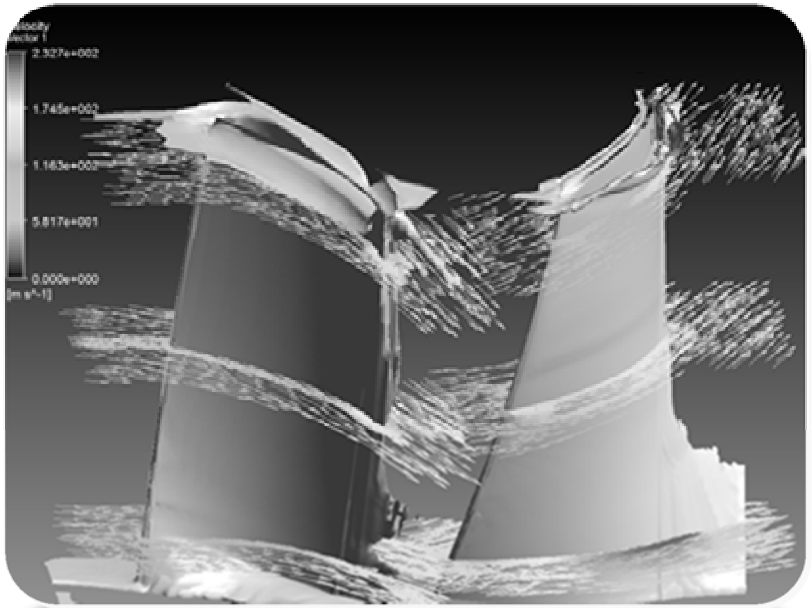
- Optimization with 560 Samples
- Optimal impeller:
    - $Mach\ Number = 0{,}95$ ✓
    - $\sigma_V = 416\ MPa$ ✓
    - $\Pi = 2{,}4$ ✓
    - $\eta = 84\ \%$ ✓

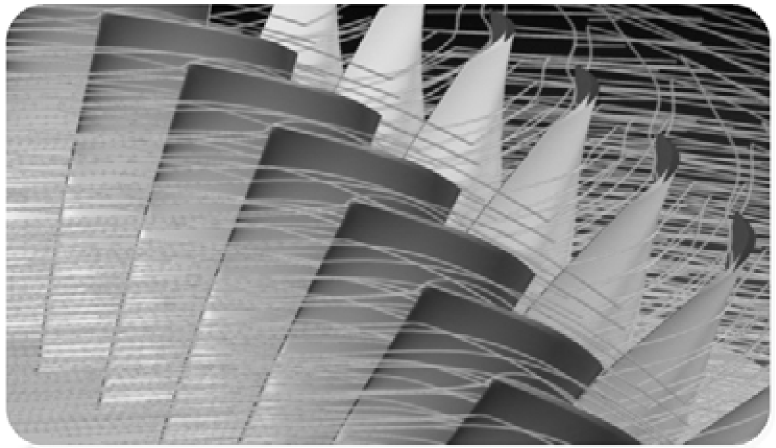
Contents

Three Dimensional Turbine Optimization

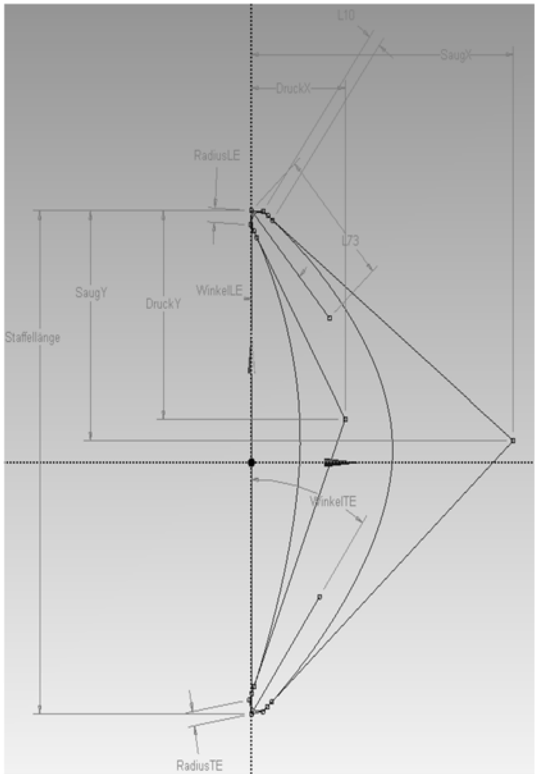
3d CFD optimization of a Turbine stage



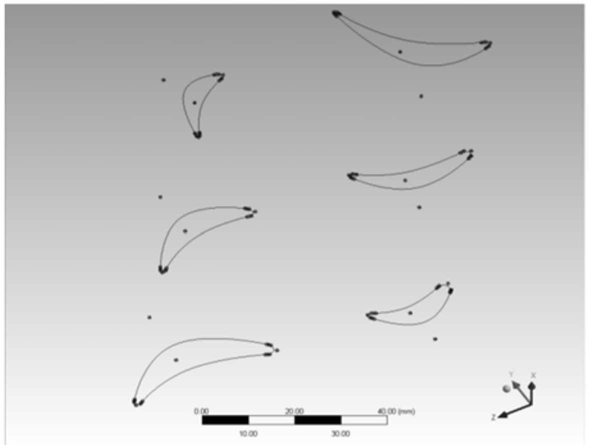


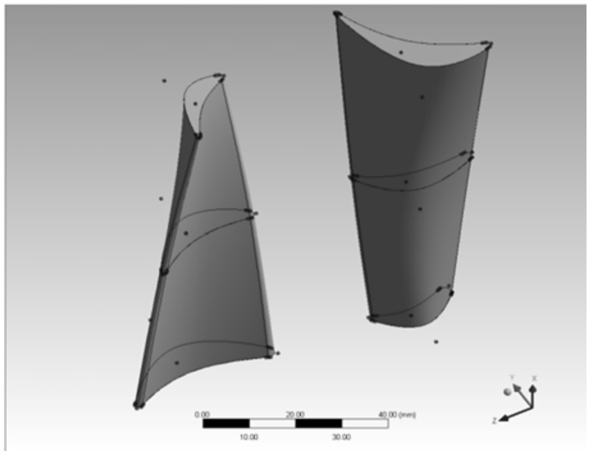


Modelling



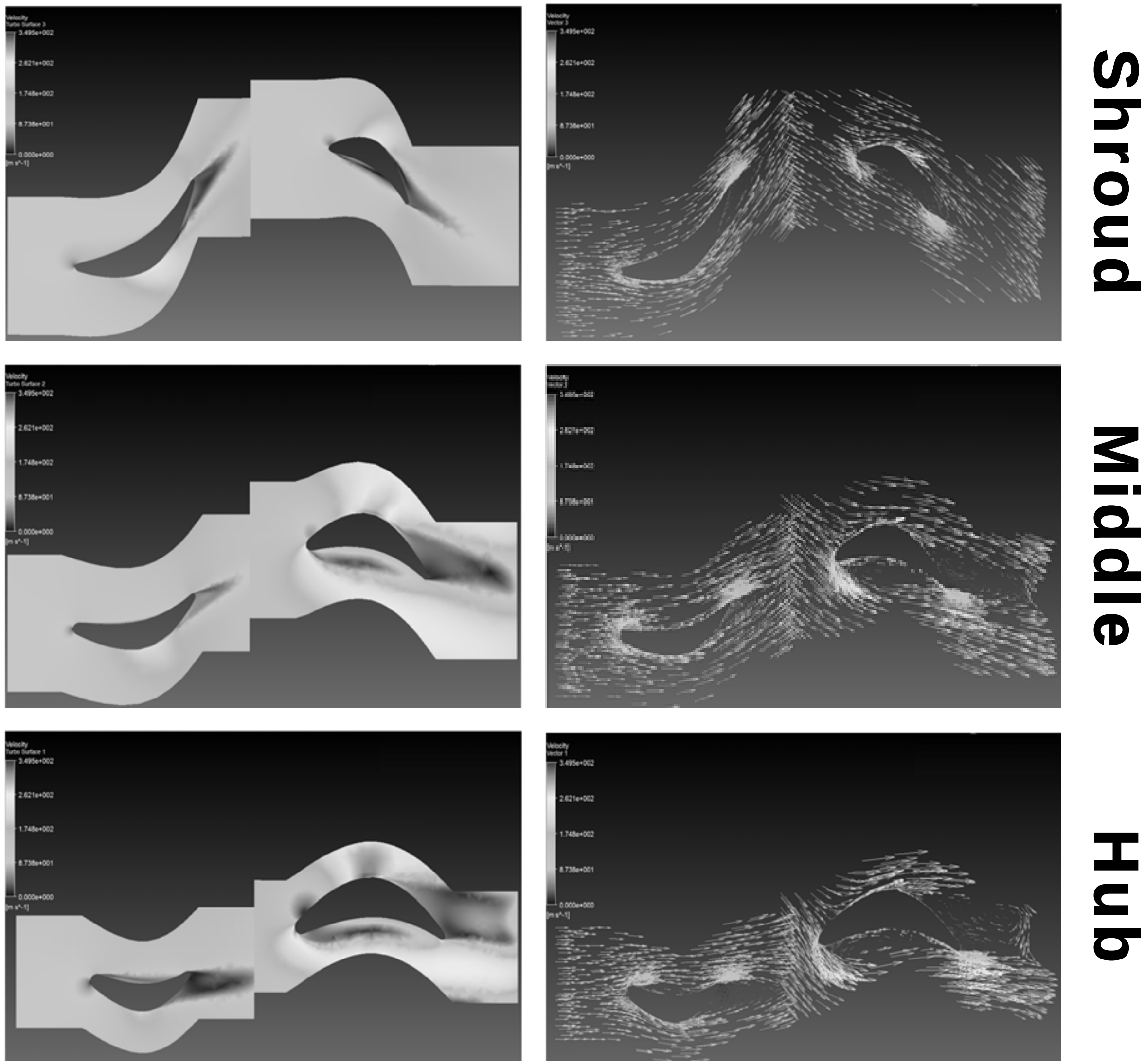
- Fully parameterized aerofoils for impeller and guide vanes
- Twisted blades
- 7 parameters per aerofoil
- Interaction of impeller and guide vanes taken into account





Results

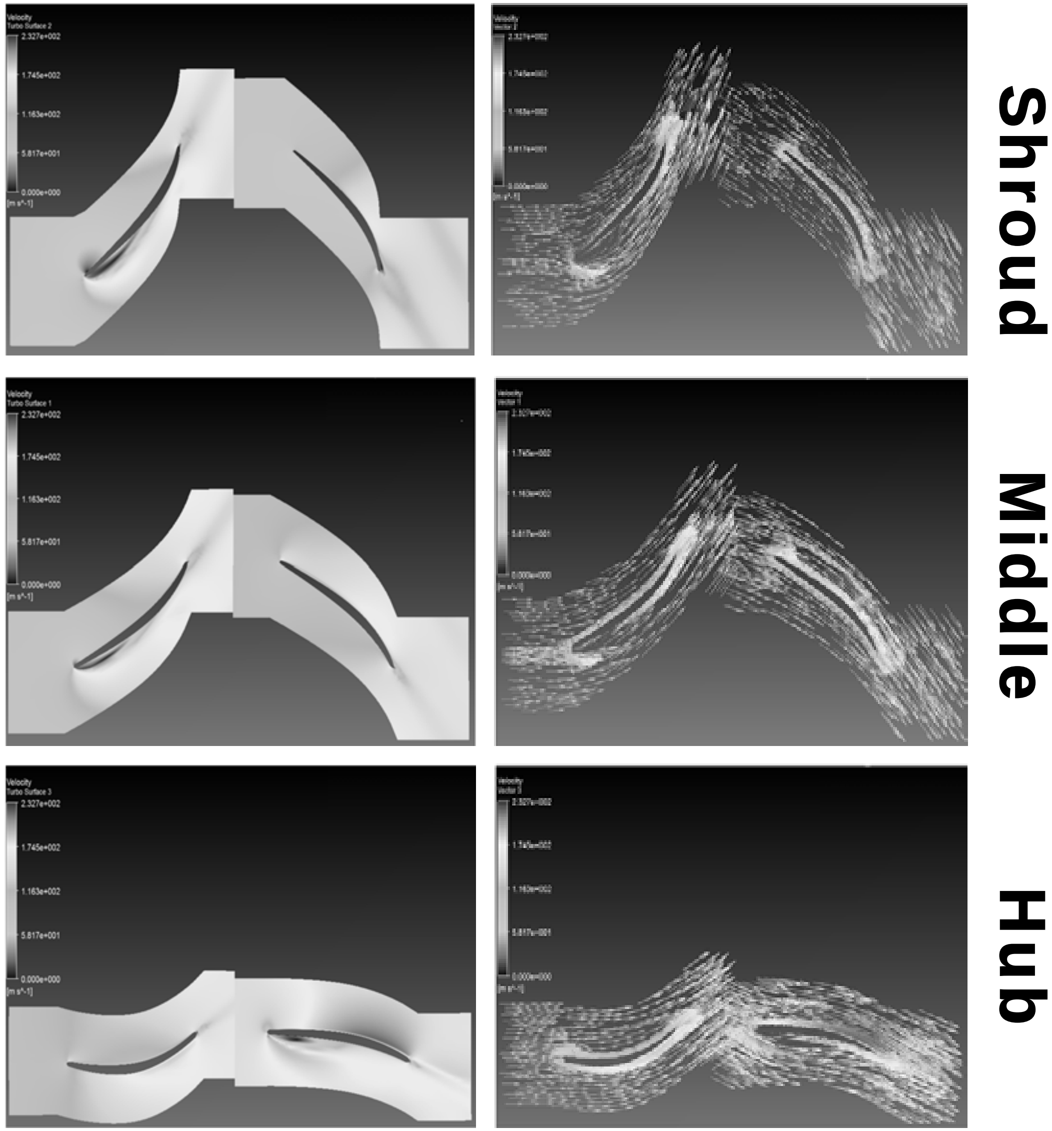
- Strong wake in the whole stage
- Polytrophic efficiency of 73%
- Pressure ratio of 0.87



Baseline Geometry

Results

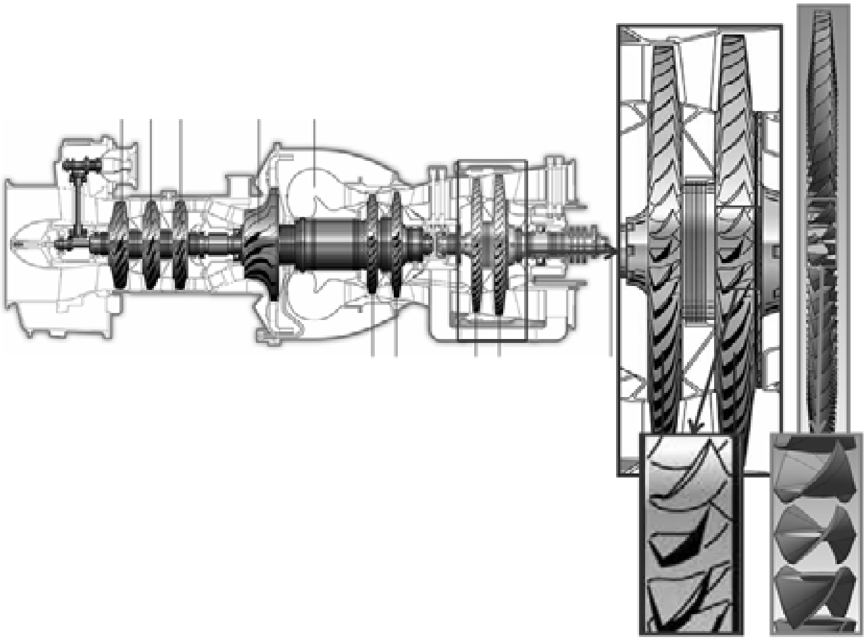
- Nearly no wake
- Polytrophic efficiency of 89%
- Pressure ratio if 0.81

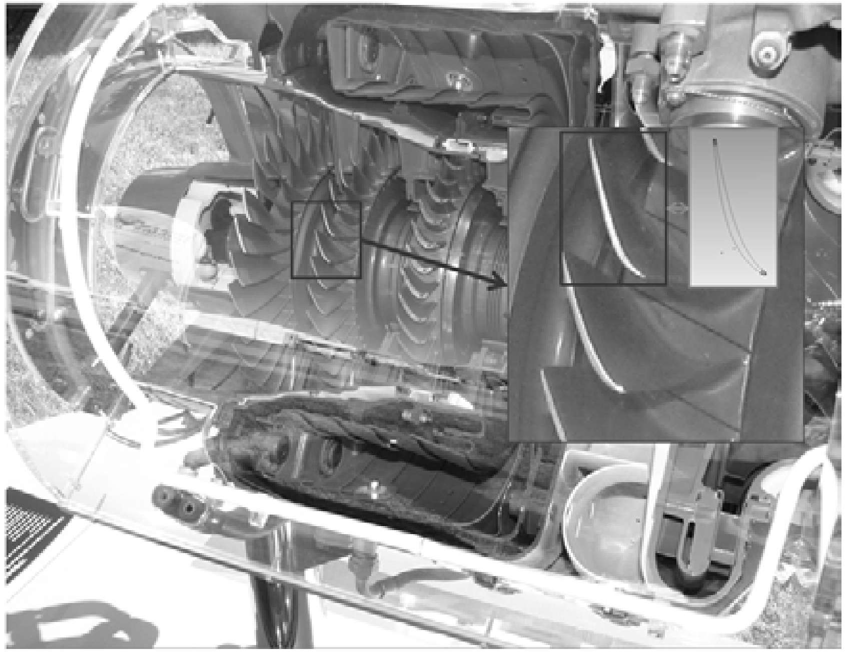


Optimized Geometry

Results

Comparison of the optimal design with existing machines
→ Good correlation of the blade design



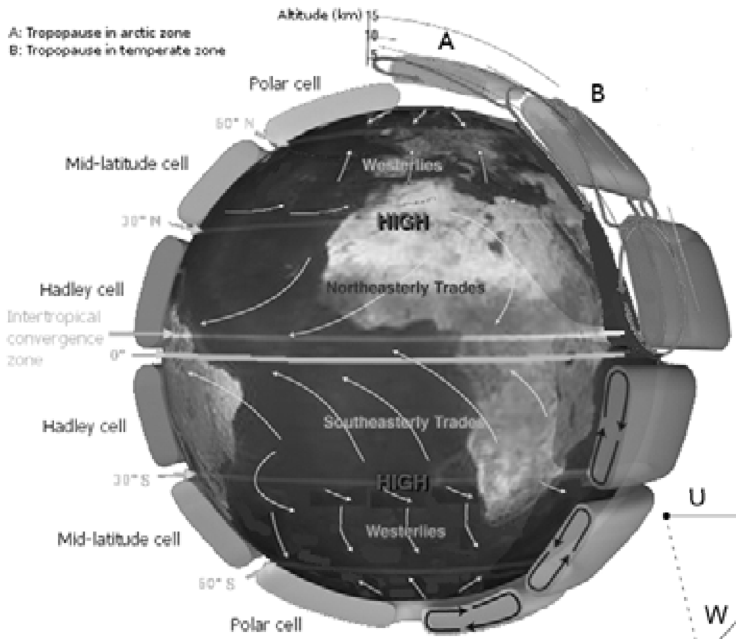


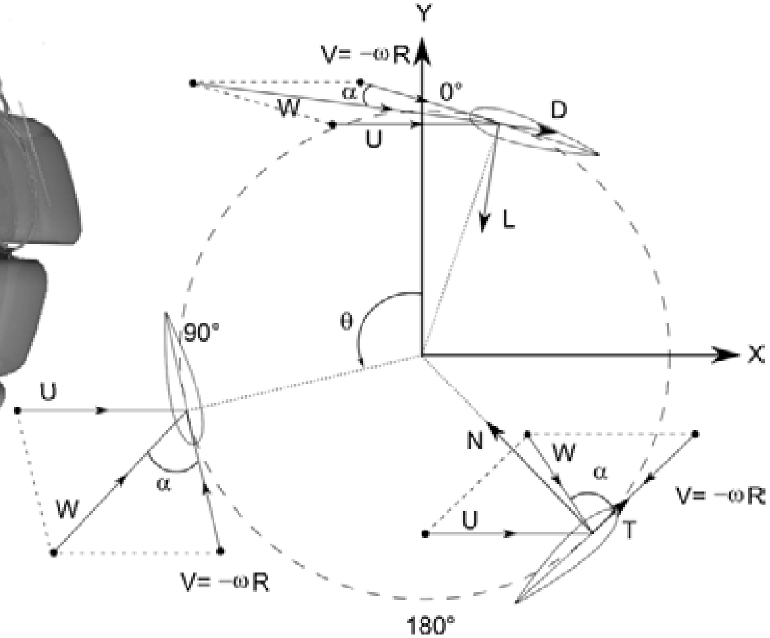
Helicopter engine

Small plane engine

CONTENTS

Introduction

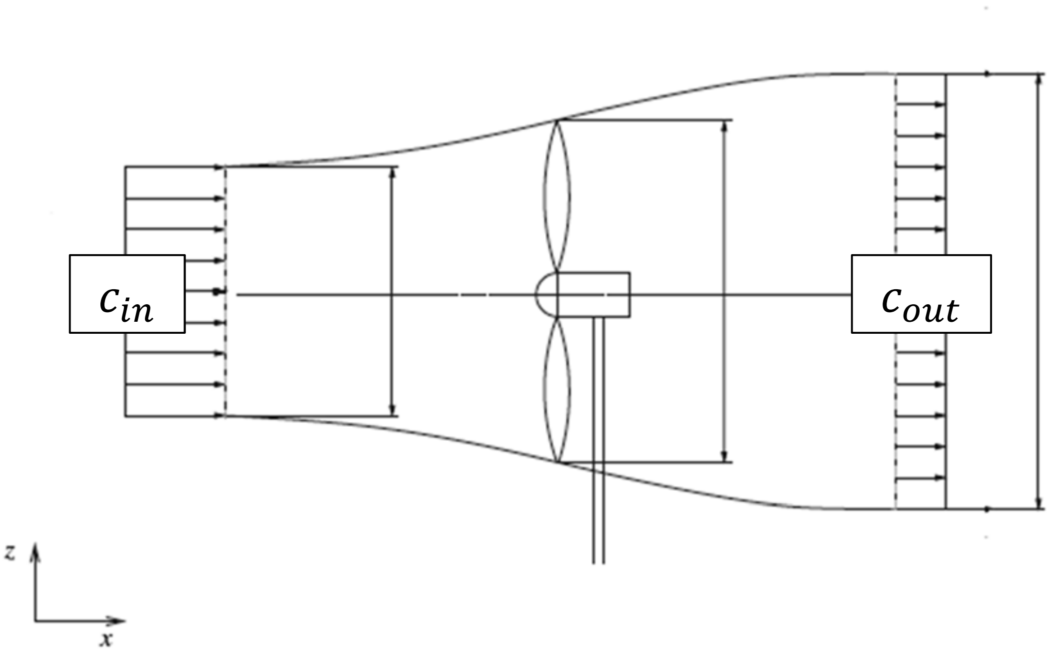




Advantages of Vertical Axis Wind Turbines (VAWT):

- Lower cost compared to horizontal axis wind turbines
- Independent of wind direction
- Good efficiency for lower wind speeds

Theory



Mechanical Power:

$$P_{mech} = \frac{1}{2}\rho A {c_{in}}^3 \left[\frac{1}{2}(1+k)(1-k^2)\right]$$

with deceleration ratio $k = \frac{c_{out}}{c_{in}}$

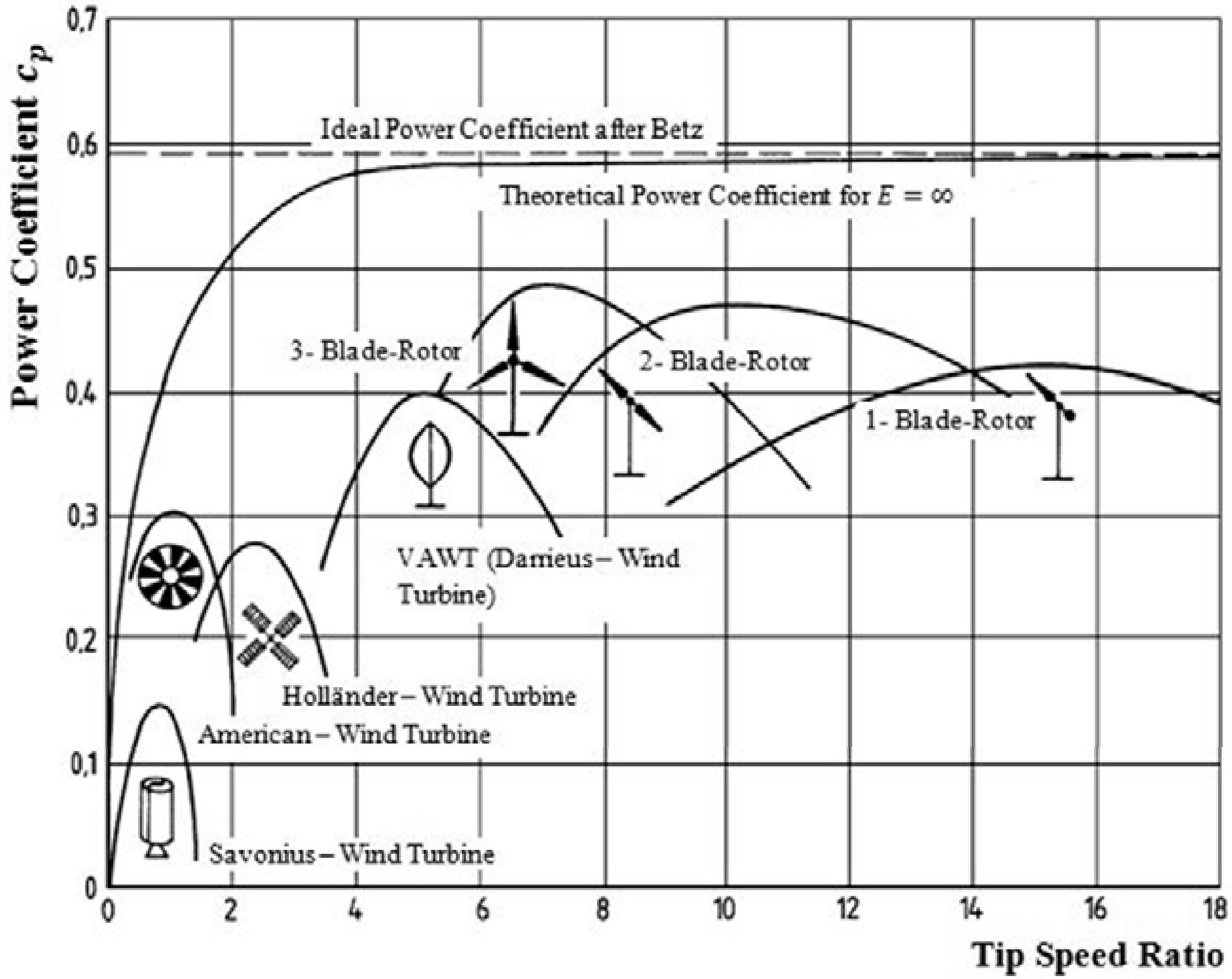
Power coefficient:

$$c_p = \frac{1}{2}(1+k)(1-k^2)$$

Theoretical maximum for $k = \frac{1}{3}$

$c_{p,Betz} = \frac{16}{27} \approx 0{,}593$ (Betz' Law)

Theory

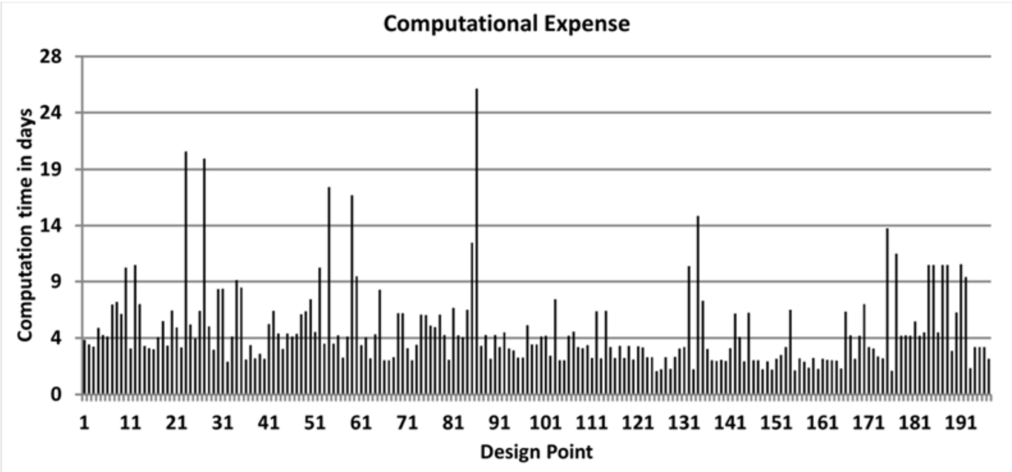


Theoretical and actual power coefficients for different wind turbines

Motivation

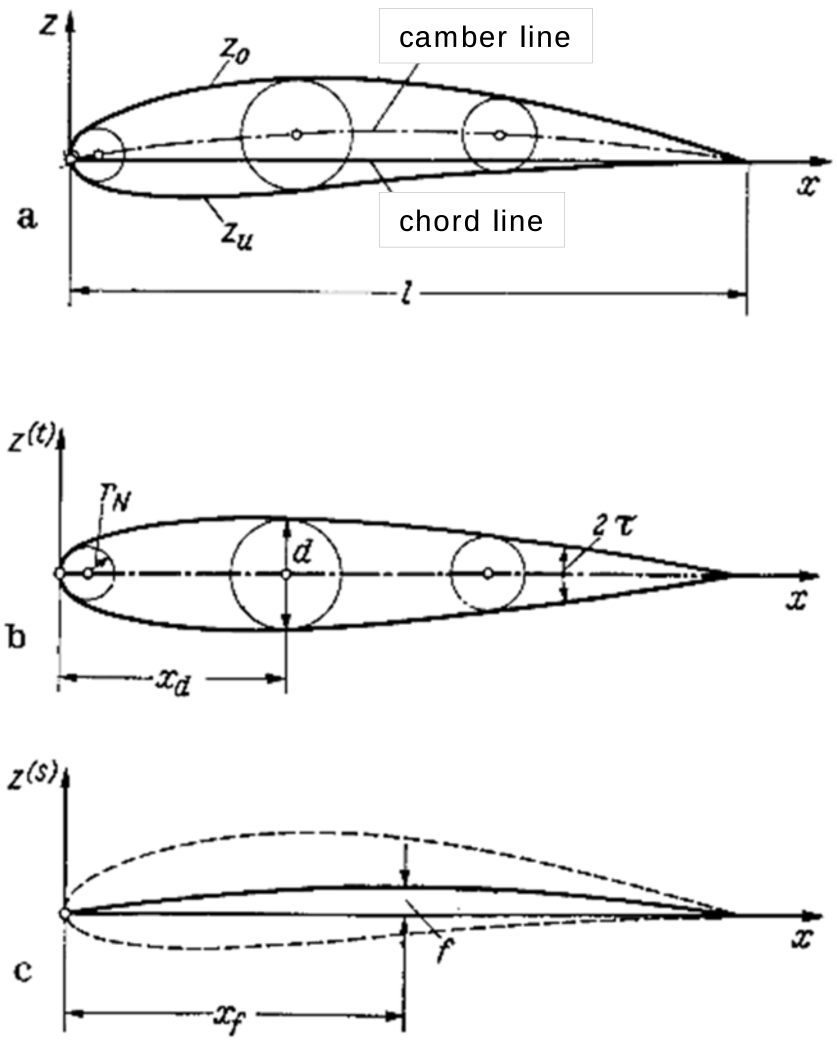
- Prediction with analytical methods is very vague
  → **CFD approach needed**
- Unsteady flow → Transient simulations are required
- Large scale machinery → High grid size

→ **High computational expense**



Solution: ***A high-quality metamodel admits efficient optimizations!***

Modelling

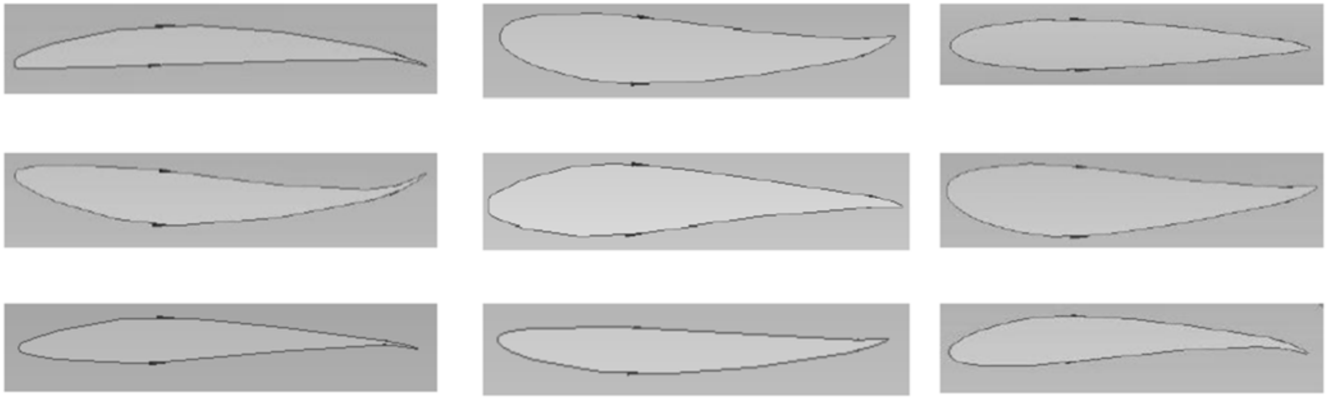


Parameterization according to Aerofoil Theory:

- Relative thickness $\frac{d}{l}$
- Relative camber $\frac{f}{l}$
- Relative distance of maximum thickness from the leading edge $\frac{x_d}{l}$
- Relative distance of maximum camber from the leading edge $\frac{x_f}{l}$
- Relative leading edge radius $\frac{r_n}{l}$
- Relative trailing edge radius $\frac{r_h}{l}$

Modelling

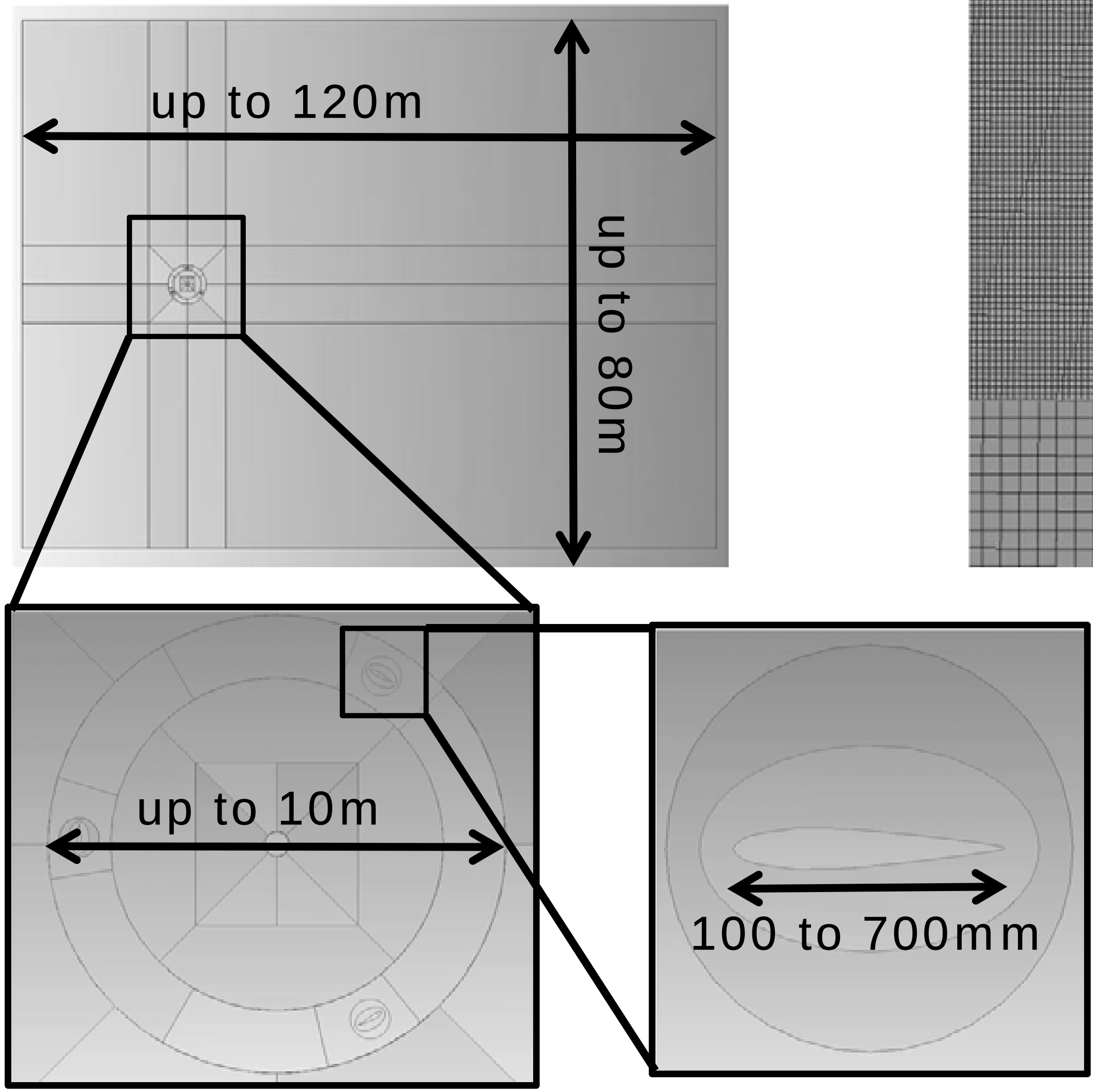
Variation of the aerofoil geometry

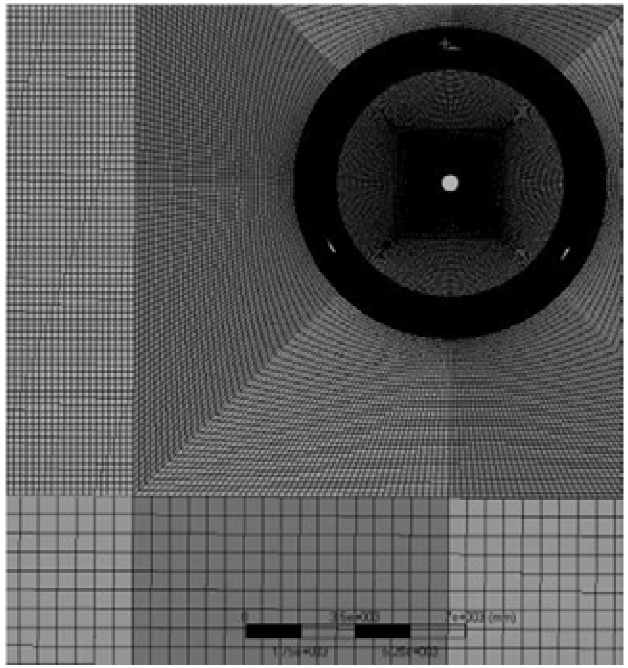


Further parameters:

- Wind turbine diameter
- Aerofoil size ratio
- Wind speed

Modelling

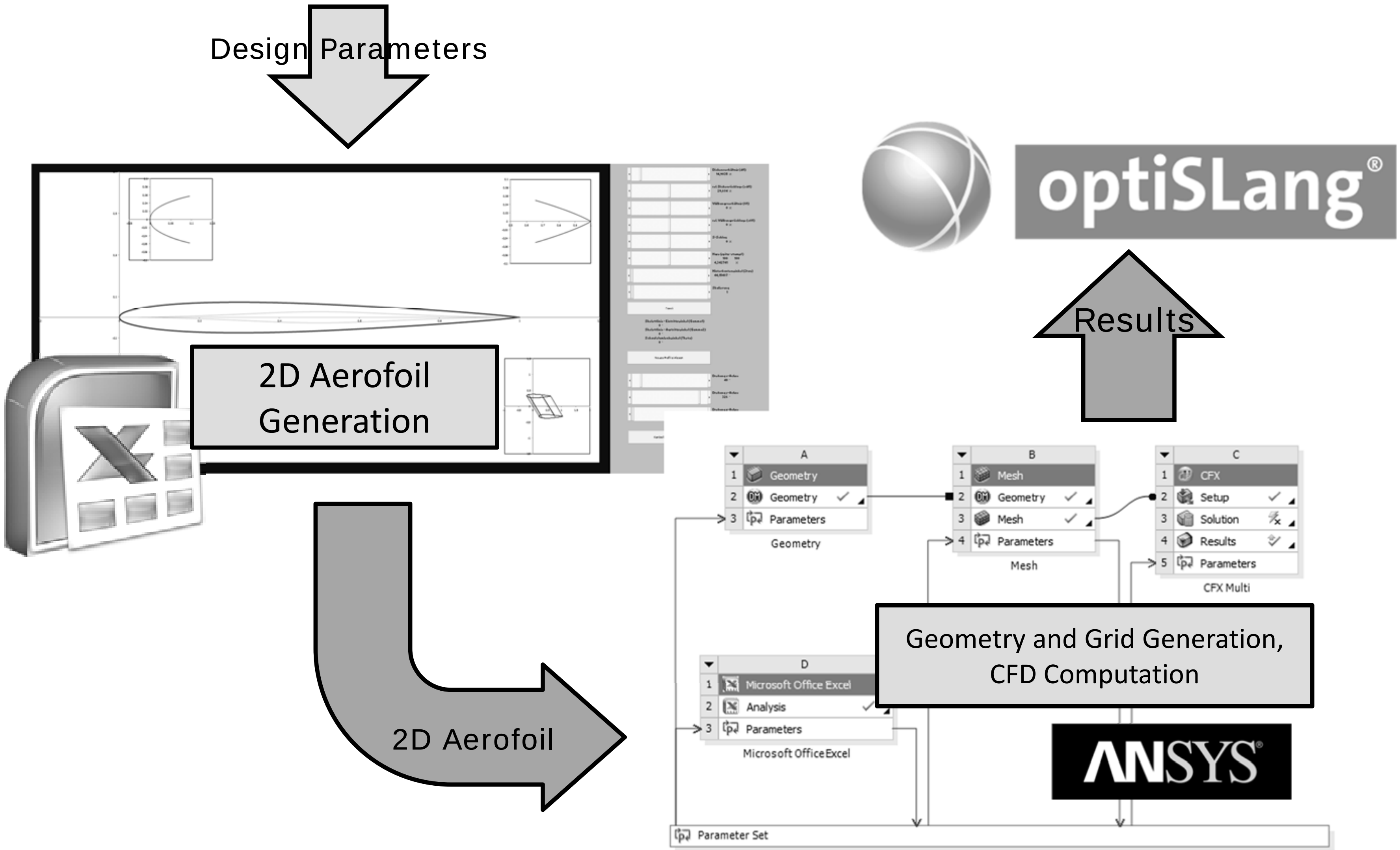




Different geometric scales have to be represented by the grid

→ High grid size

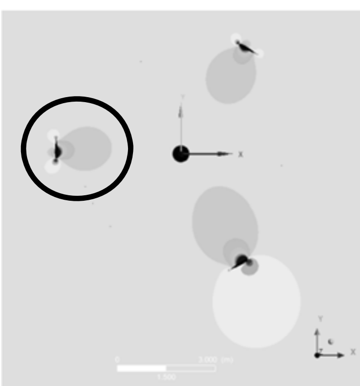
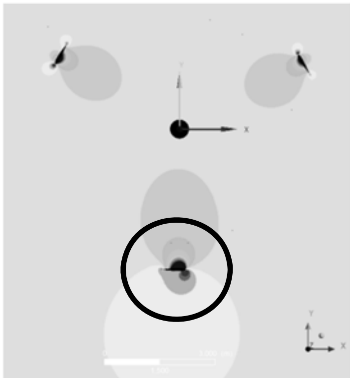
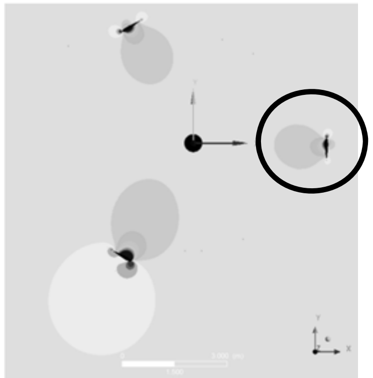
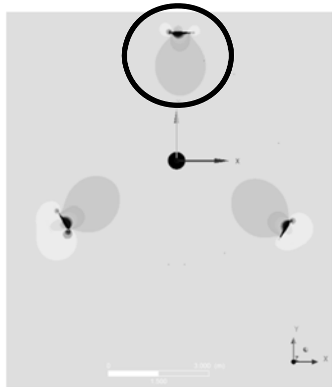
Process

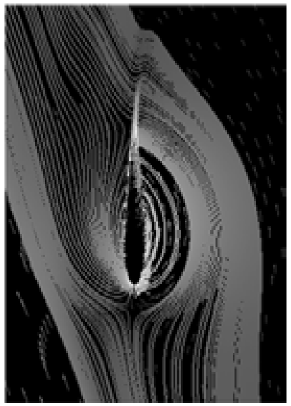

Design Parameters
2D Aerofoil
Generation
2D Aerofoil
optiSLang®
Results
A
Geometry
Geometry
Parameters
Geometry
B
Mesh
Geometry
Mesh
Parameters
Mesh
C
CFX
Setup
Solution
Results
Parameters
CFX Multi
D
Microsoft Office Excel
Analysis
Parameters
Microsoft Office Excel
Geometry and Grid Generation,
CFD Computation
ANSYS
Parameter Set

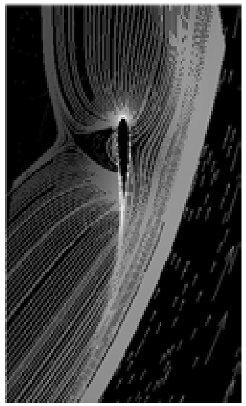
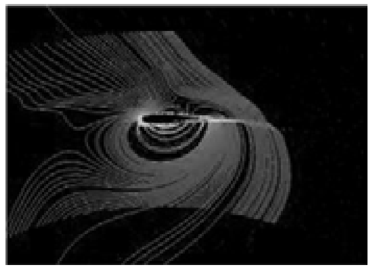
Results

Flow field for one rotor revolution

(As seen in video, video can be provided on request)

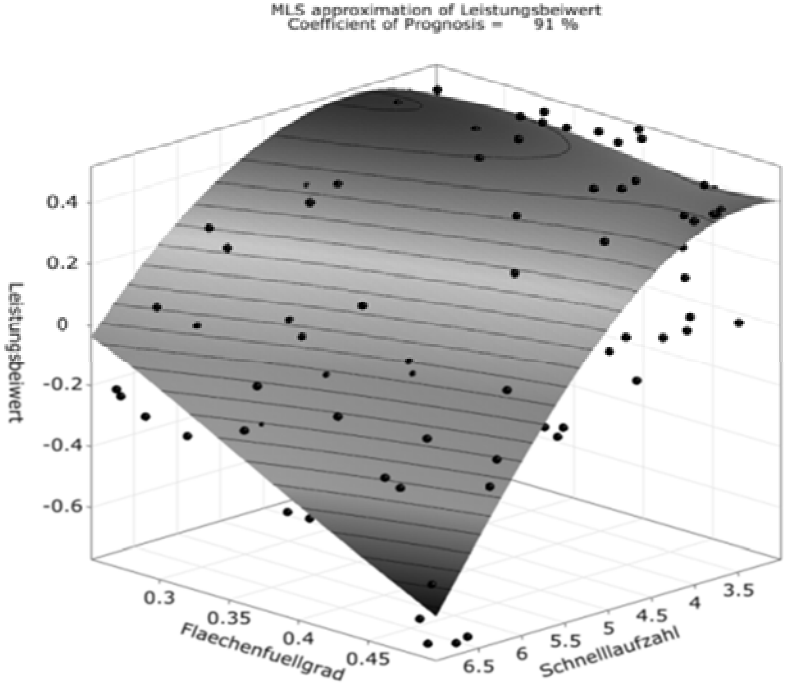





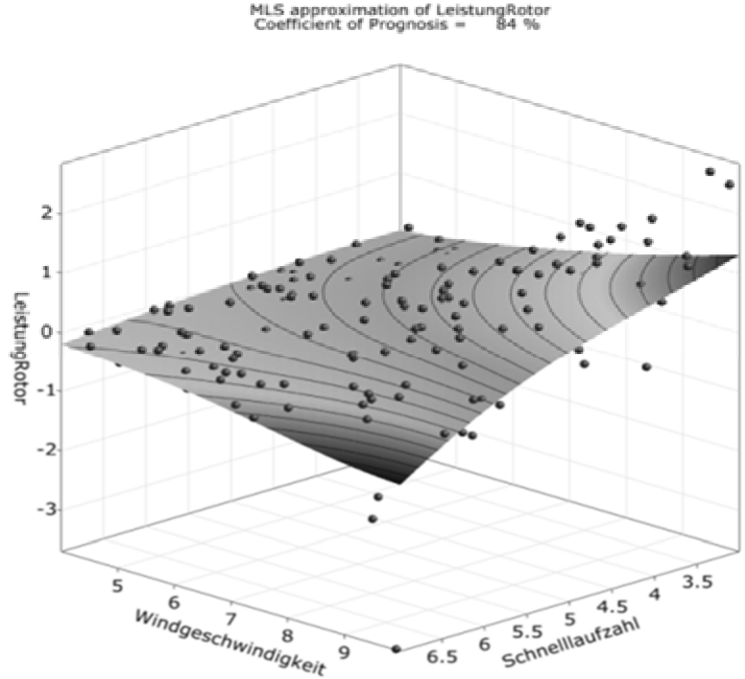


Results

MLS – Approximation of the Efficiency / Power Output
based on the Meta Model of optimal Prognosis (MoP)



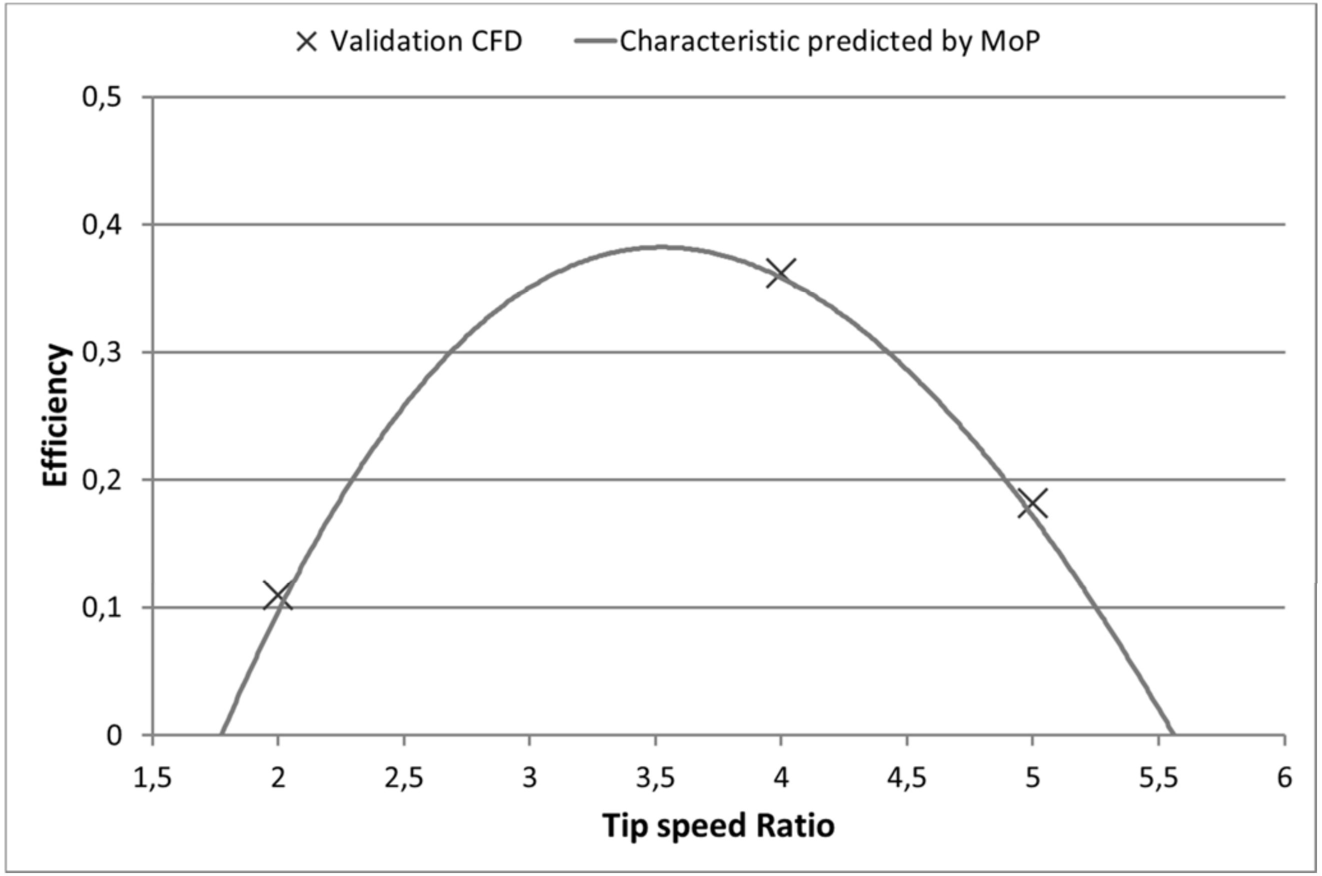


High CoP for both Efficiency and Power Output

(CoP = 91%) (CoP = 84%)

Results

Validation of the metamodel against CFD calculations



Results

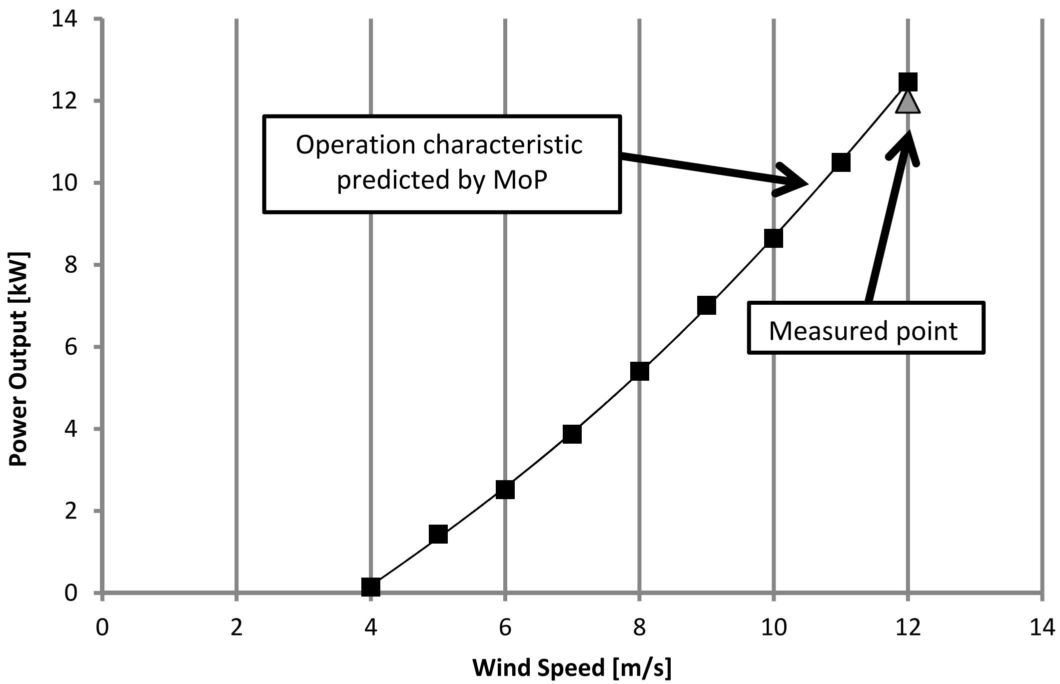
Validation of the metamodel against an existing Machine

Aerofoil type	NACA 0021
Aerofoil length	250 mm
Number of wings	3
Rotor radius	3 m
Rotor height	5 m
Tip speed ratio	4
Nominal wind speed	12 m/s
Nominal Power Output	12 kW

Marsta-VAWT – University of Uppsala

Results

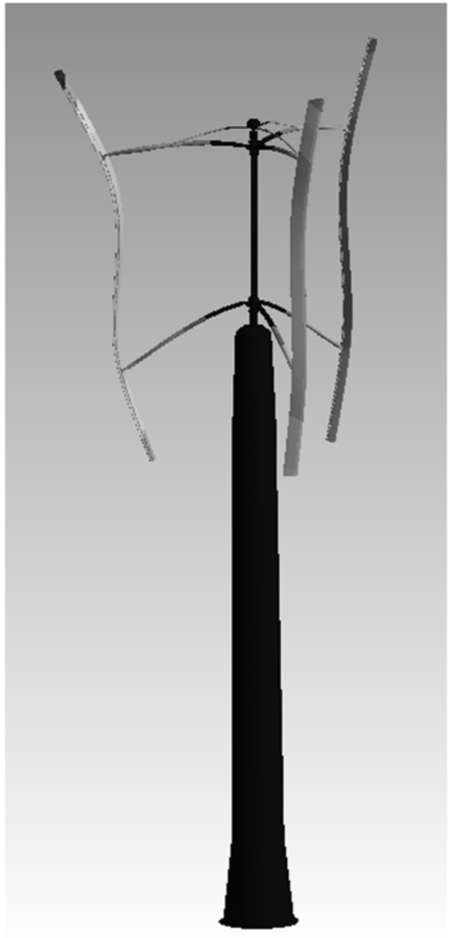
Validation of the metamodel against an existing Machine

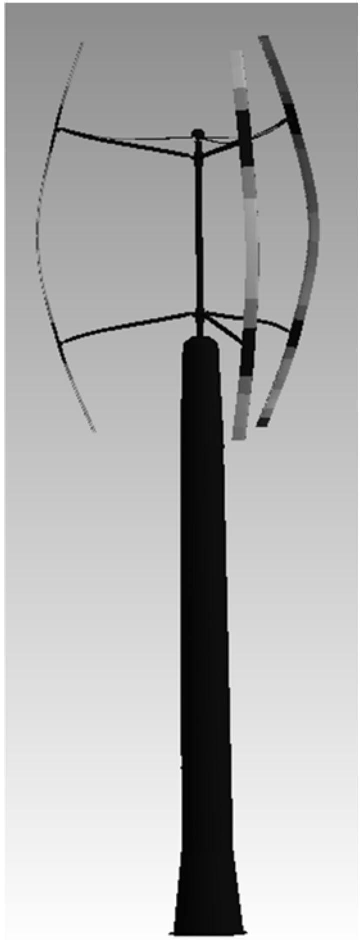


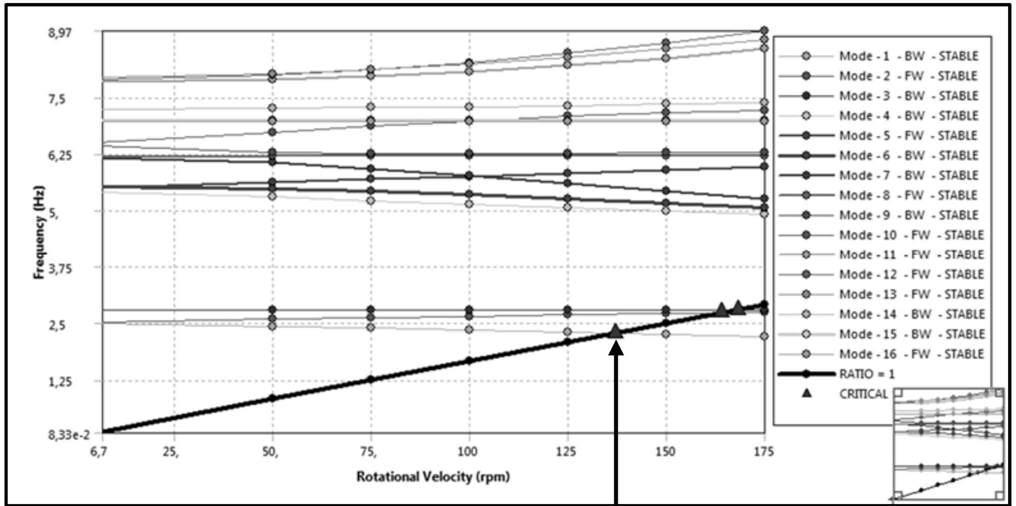
Marsta-VAWT – University of Uppsala

Results

FEA – Frequency Anlysis







First critical frequency occurs at 132rpm
Nominal operation range: 50 – 100rpm

→ **Safe Operation can be guaranteed!**

Summary

- 200 CFD Designs calculated
- Metamodel with high CoP
- Metamodel validated with additional CFD caluclations
- Metamodel validated against existing machines
- Operation characteristics of arbitrary machines can be predicted natively in optiSLang
  without further CFD Simulations!