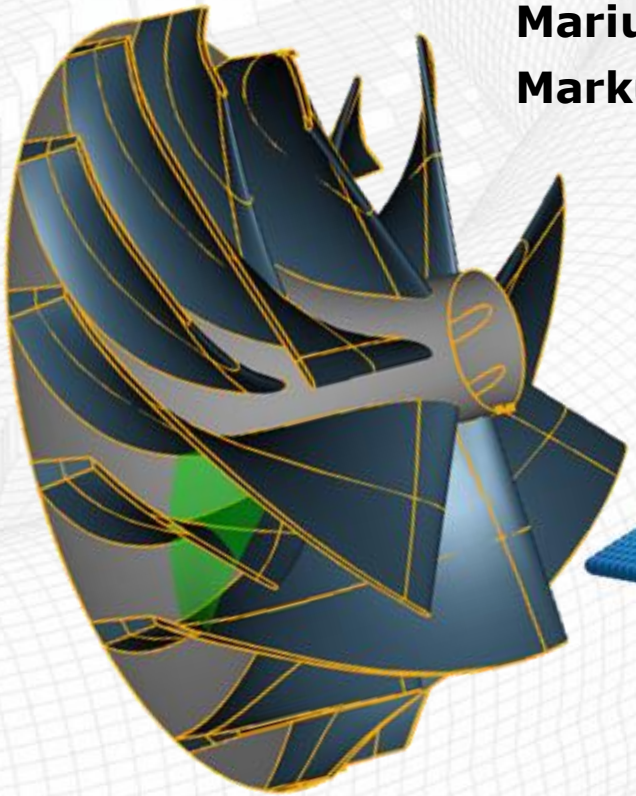
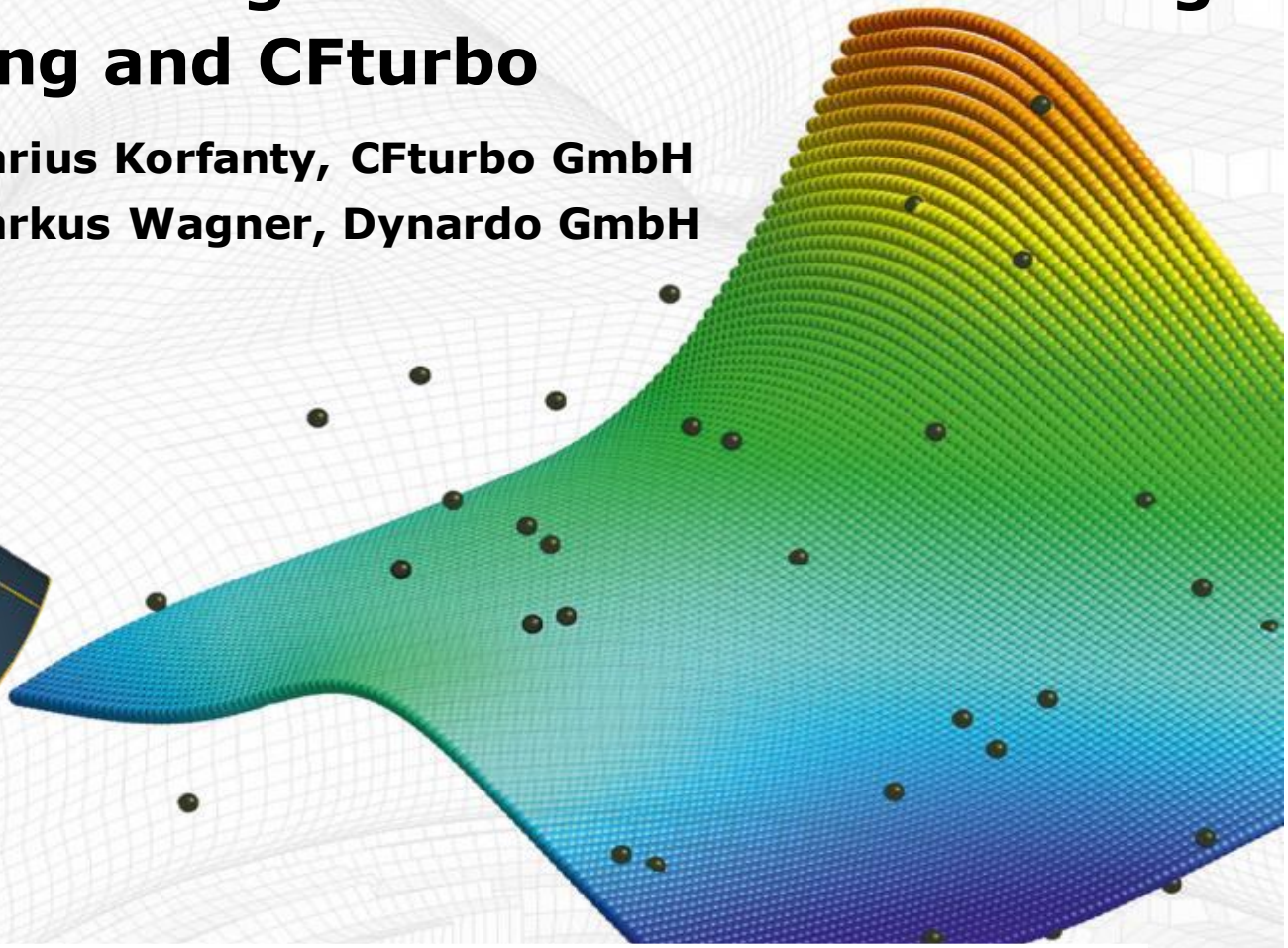
Optimization and design of turbo machines using ANSYS optiSLang and CFturbo

Marius Korfanty, CFturbo GmbH
Markus Wagner, Dynardo GmbH





Outline

- Introduction into optiSLang and CFturbo
- I : Optimization of an axial pump (M. Korfanty, CFturbo GmbH)
  - Aim of analysis
  - CAE Workflow
  - Sensitivity analysis
  - Optimization
  - Summary
- II : Performance map analysis of a radial compressor (M. Wagner, Dynardo GmbH)
  - Aim of analysis
  - CAE Workflow
  - Sensitivity analysis
  - Optimization on MOP
  - Summary

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Dynardo

- Founded: 2001
- More than 60 employees, offices at Weimar and Vienna
- Leading technology companies Daimler, Bosch, ZF/TRW, Siemens are supported

Software Development

optiSLang® SoS® multiPlas

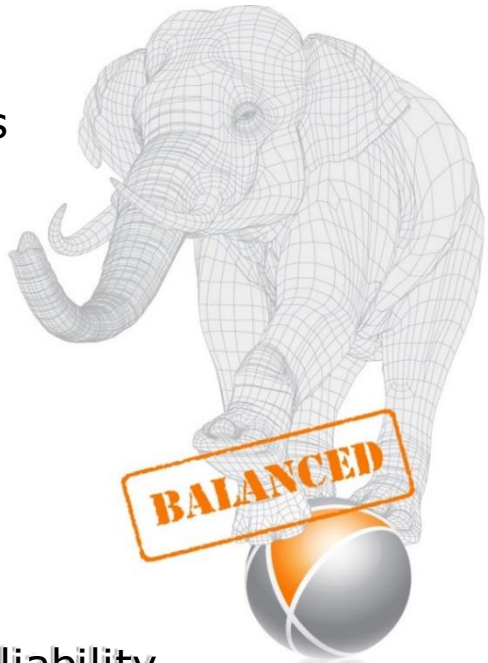
Dynardo is engineering specialist for CAE-based sensitivity analysis, optimization, robustness evaluation and robust design optimization

CAE-Consulting

- Mechanical engineering
- Civil engineering & Geomechanics
- Automotive industry
- Consumer goods industry
- Power generation

optiSLang

- is a **general purpose tool** for variation analysis



using CAE-based design sets (and/or data sets) for the purpose of

- sensitivity analysis
- design/data exploration
- calibration of virtual models to tests
- optimization of product performance
- quantification of product robustness and product reliability
- Robust Design Optimization (RDO) and Design for Six Sigma (DFSS)

serves arbitrary CAX tools with
- **support of process integration**
- **process automation**
- **workflow generation**

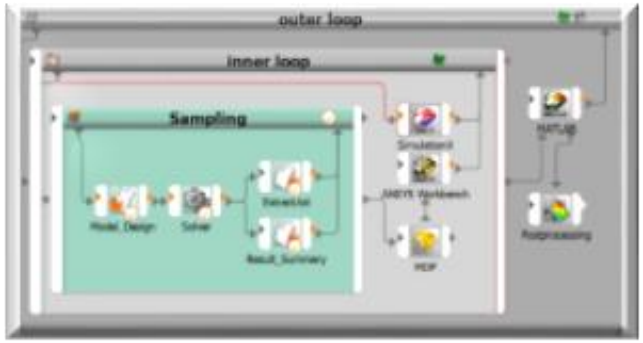
SPDM

Input 1

Input 2

Input n

Workflow-Management



with
Process Integration
and for
Automatization

Output 1

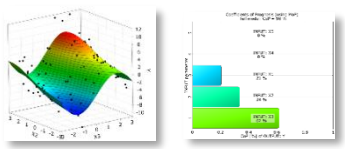
Output 2

Output m

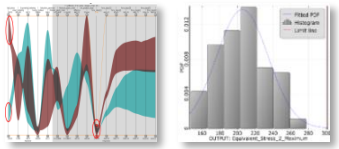
Excel Add-In

ANSYS optiSLang

other Solver



Postprocessing

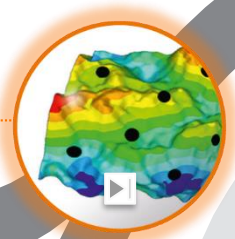


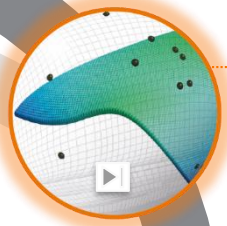
Design Understanding

Investigate parameter sensitivities, reduce complexity and generate best possible meta models

Design Improvement

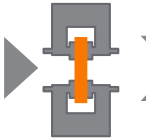
Optimize design performance



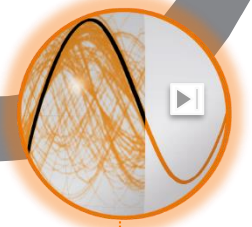


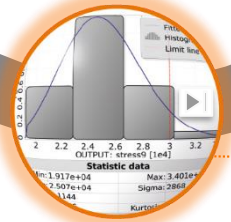
CAE-Data

Robust Design



Measurement Data





Model Calibration

Identify important model parameters for the best fit between simulation and measurement

Design Quality

Ensure design robustness and reliability

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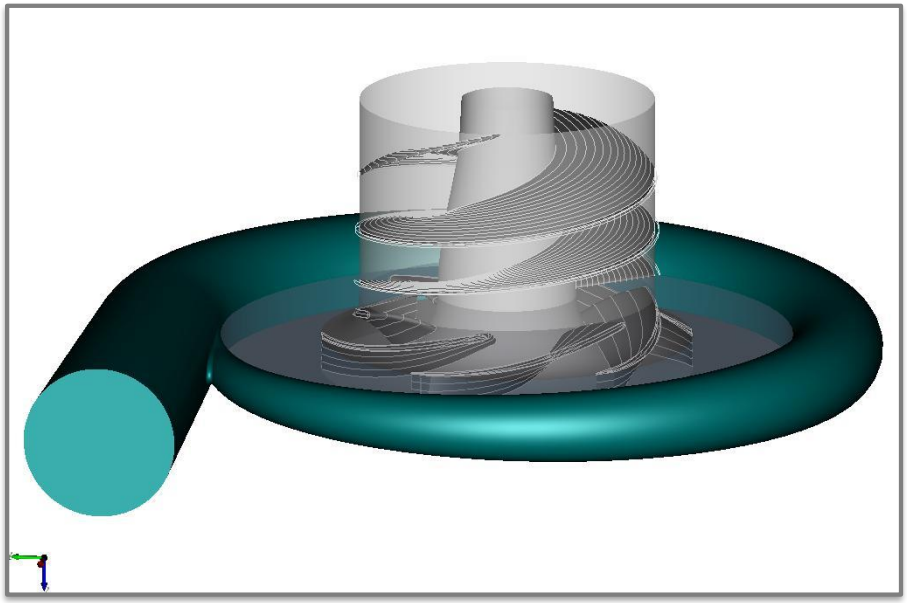
Design Software

- CFturbo® is a modern, powerful and user-friendly software for **Conceptual Turbomachinery Design**
- 160 active clients globally
- CFturbo® modules to design
  - Pumps
  - Blowers
  - Compressors
  - Turbines
  - Stators and diffusers
  - Volutes



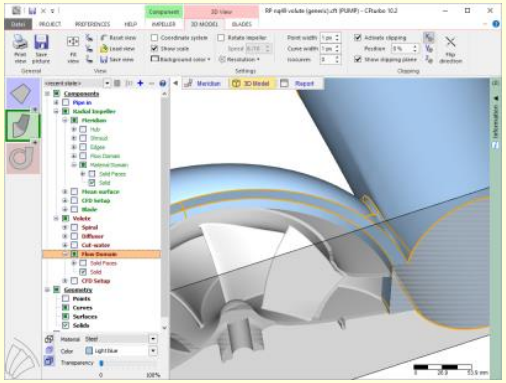
- **Industries**: Aerospace, Automotive, Consumer Products, Energy, Oil & Gas, Marine, Mechanical & Process Engineering, Semiconductor,

Company structure

CFturbo® GmbH

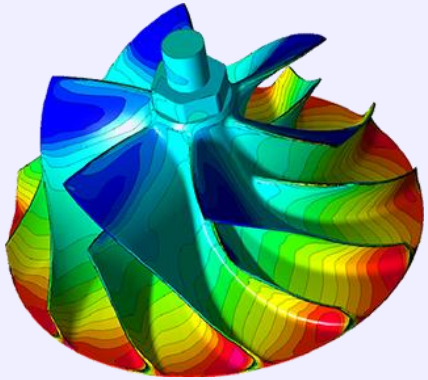
❶ CFturbo® Software

- Conceptual Design Software
- Custom development
- Training



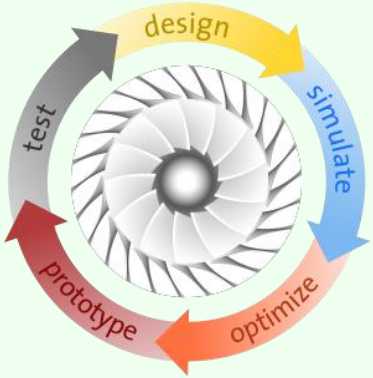
❷ CAE Consulting

- Turbomachinery Design
- Flow & strength simulation (CFD,FEA)



❸ Workflows

- Automated CAE workflows
- DOE
- Optimization



I Aim of analysis

Design point

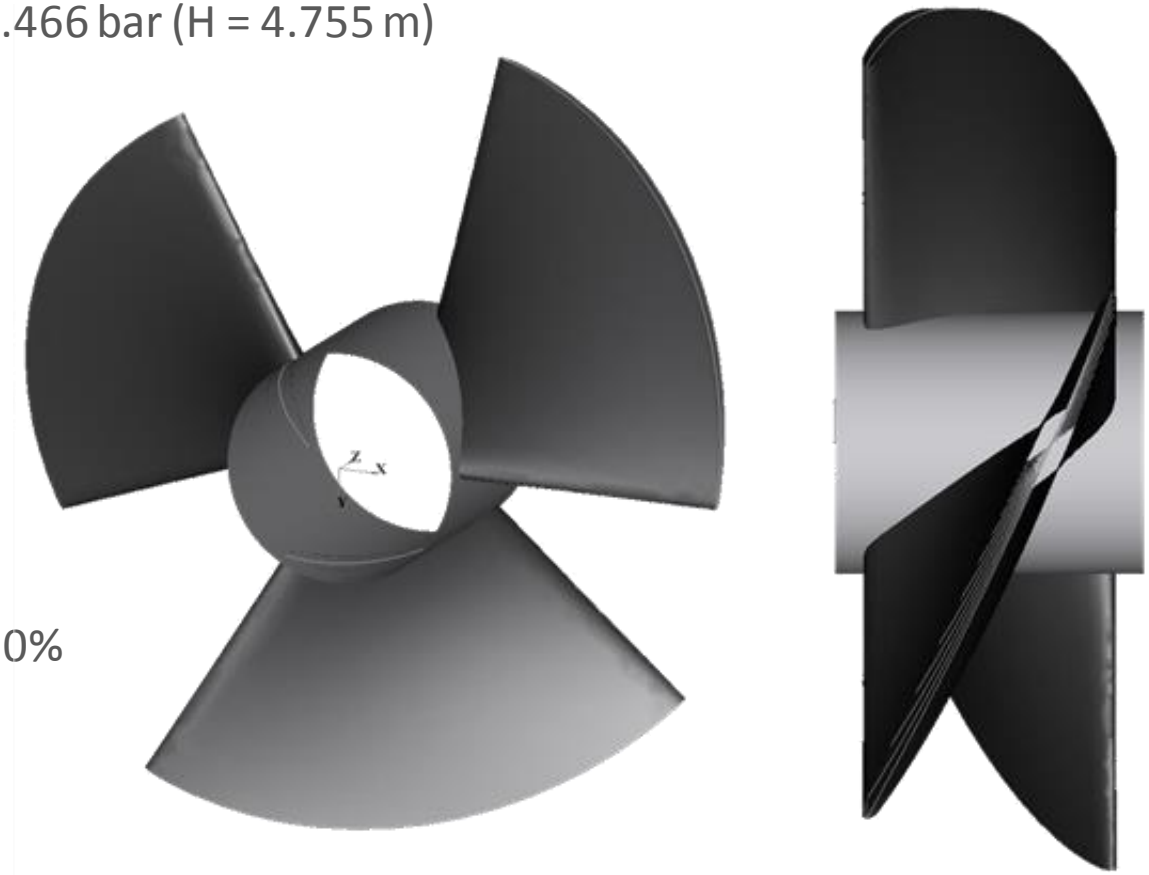
- Flow rate Q = 1.476 m³/s
- Total pressure difference Δp_t = 0.466 bar (H = 4.755 m)
- Rotational speed = 780 rpm
- Water, no pre-swirl

Objective

- **Max. hydraulic efficiency η**

Constraints

- $\beta_{B2} < 90°$
- Total pressure difference $\Delta p_t \pm 10\%$



I CAE Workflow – CFturbo

original_AxialPump.cft-batch

```
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                        </MainDimensionsElement>
                    </MainDimensions>
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                        <TgrMer_AImp Type="Object" Desc="Meridional contour">
                            <Bezier4MerLE Type="Object" Name="GeoLeadingEdge" Des
                                <Points Type="Points" Count="5" Desc="Control poi
                                    <Point Type="Point" Index="0">
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                                        <y Type="Float">0.0876</y>
                                    </Point>
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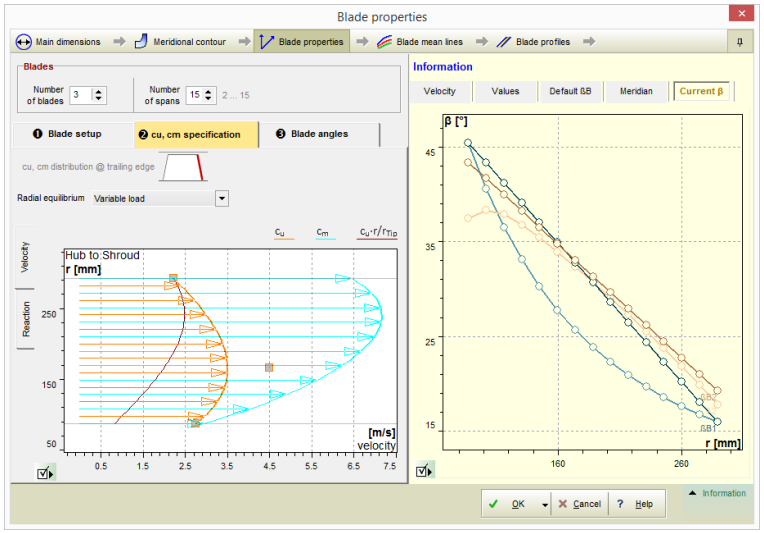
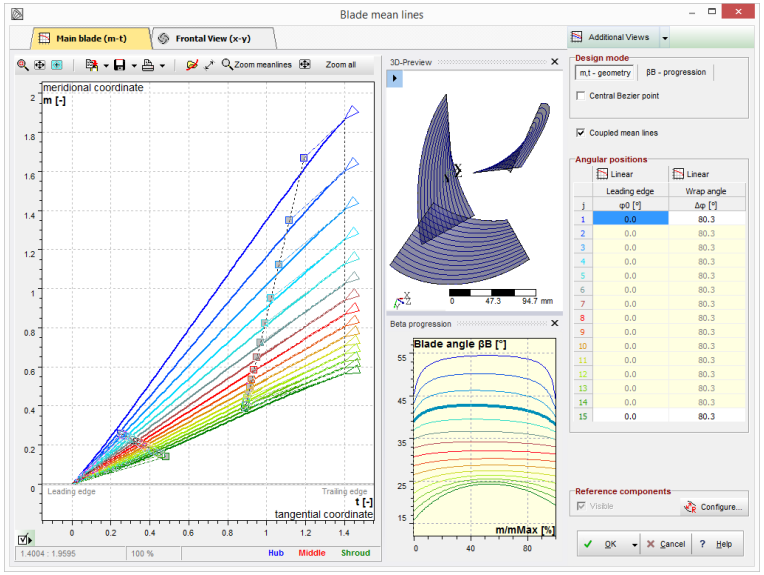




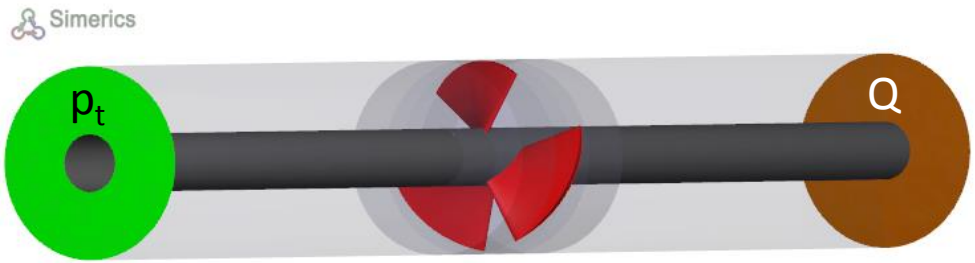
→ Fully parametric geometry model of machines

→ Each parameter can be used for optimization

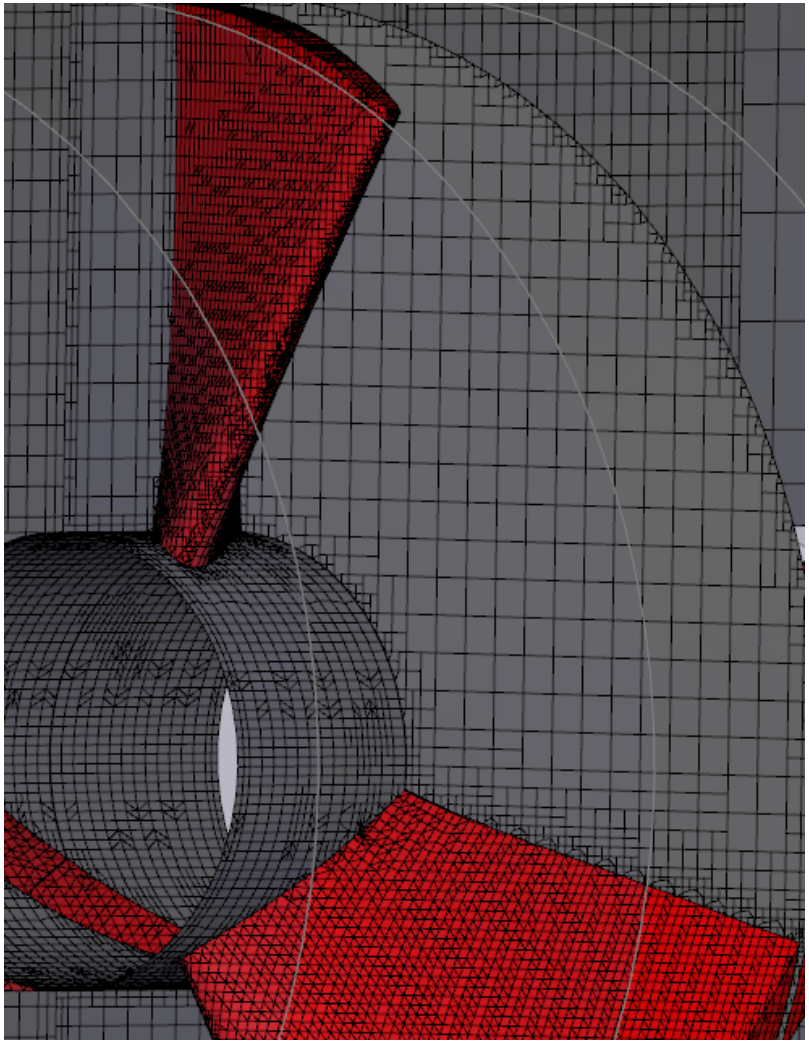
I CAE Workflow – PumpLinx

CFD system with high solver speed, especially for fluid systems with rotating/ sliding components

Geometry model with



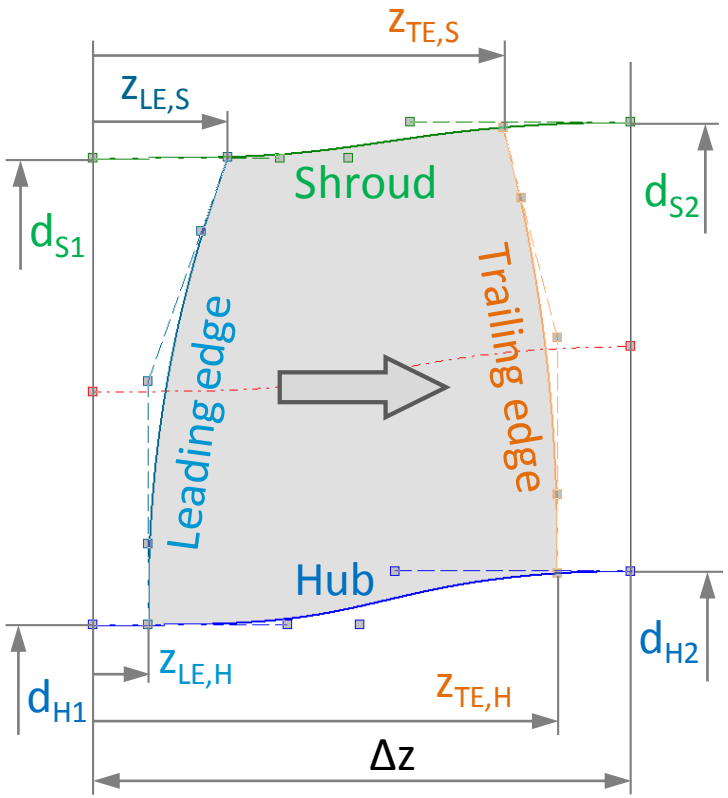
inflow region impeller outflow region

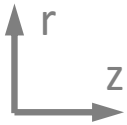


Mesh density:
292 000 nodes
200 000 cells

I CAE Workflow – Optimization parameters

	#	Parameter	Reference	Minimum	Maximum
Main dimensions	1	$d_{H1} = d_{H2}$	176 mm	140 mm	210 mm
	2	$d_{S1} = d_{S2}$	584 mm	467 mm	700 mm
		$\nu = d_{H1} / d_{S1}$	0.30	0.20	0.45
Meridional contour	3	Δz	204 mm	160 mm	320 mm
	4	$z_{LE,H}$*	0.1	0.2	0.1
	5	$z_{LE,S}$*	0.2	0.02	0.4
	6	$z_{TE,H}$*	0.9	0.8	0.9
	7	$z_{TE,S}$*	0.9	0.6	0.98





Meridional view

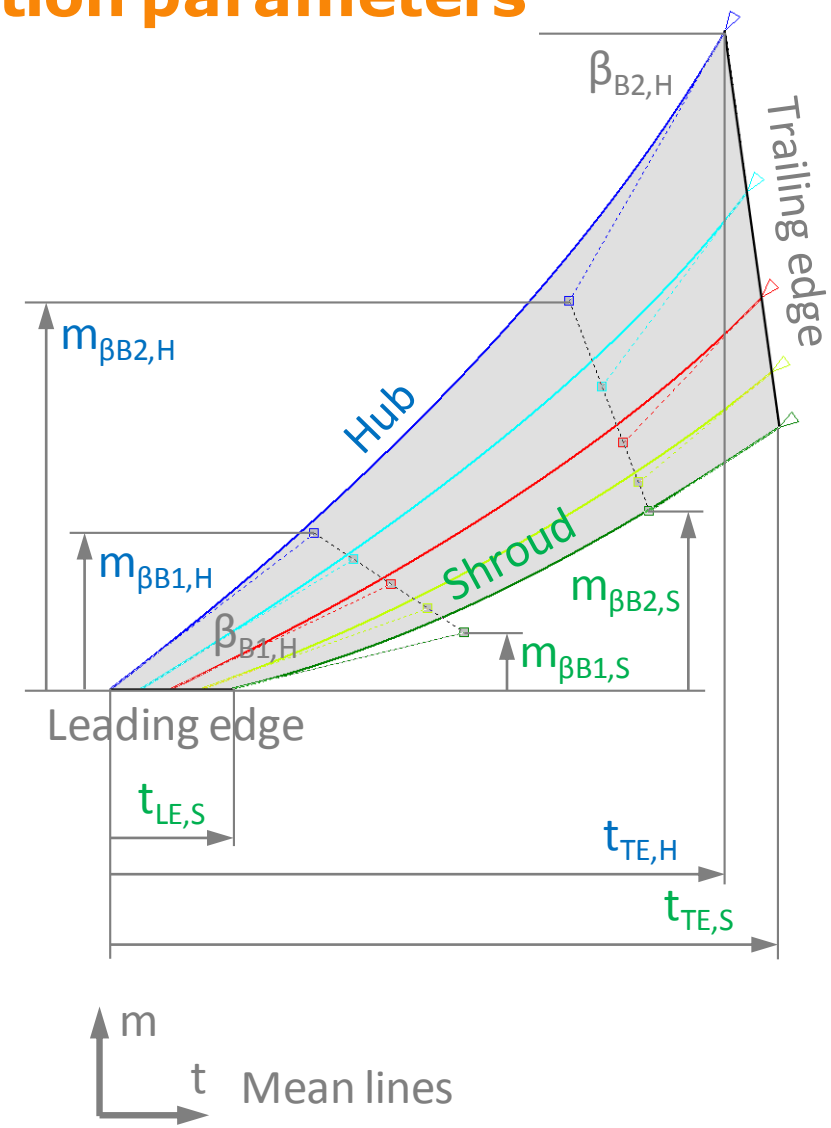
Simplifications:

- Hub and Shroud (Tip) axis-parallel
- Straight meridional leading and trailing edge

I CAE Workflow – Optimization parameters

	#	Parameter	Reference	Minimum	Maximum
Blade properties	8	n_{Bl}	3	2	6
Mean lines	9	$t_{LE,S}$	0°	-25°	25°
	10	$t_{TE,S}$	80.3°	64.25°	96.37°
	11	$t_{TE,H}$	80.3°	64.25°	96.37°
	12	$m_{\beta B1,H}$*	0.333	0.1	0.4
	13	$m_{\beta B1,S}$*	0.166	0.1	0.4
	14	$m_{\beta B2,H}$*	0.718	0.6	0.9
	15	$m_{\beta B2,S}$*	0.773	0.6	0.9

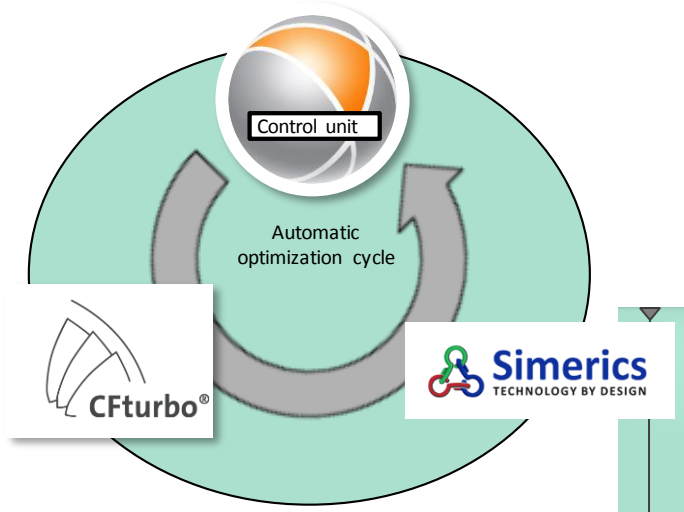
15 parameters for optimization



Simplifications:

- Free vortex velocity distribution
- Automatic calculation of blade angles β_{B1} (shock-less inflow), β_{B2} (Euler equation)

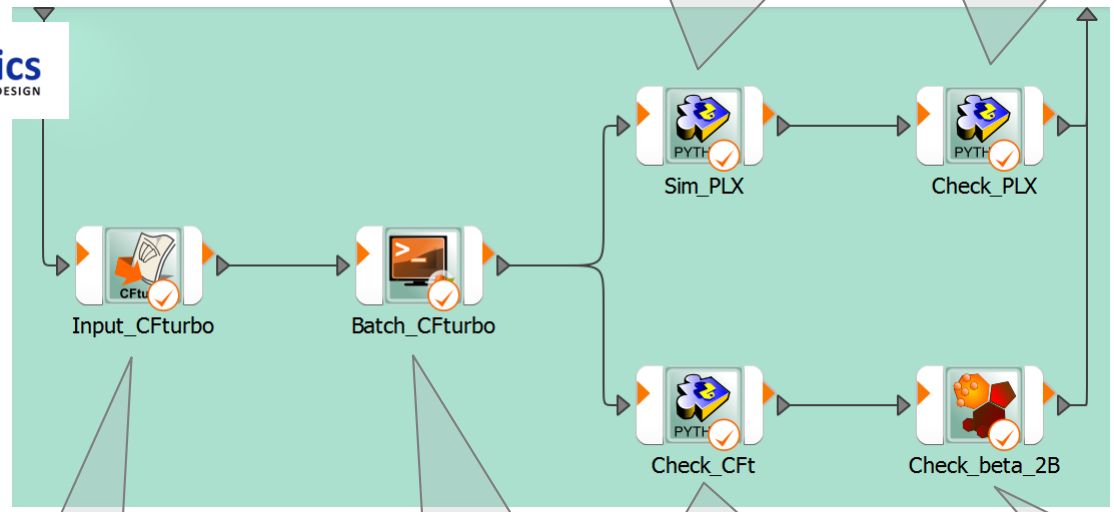
I CAE Workflow – Optimization Cycle



PumpLinx

Meshing, simulation, convergence check, interpretation

Data evaluation



CFturbo

Variation of geometry parameters

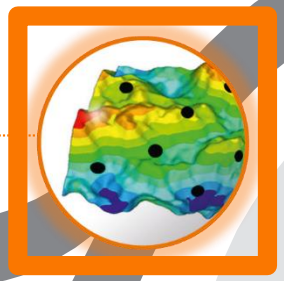
Geometry update & export (*.spro, *.stl)

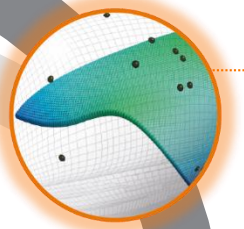
Check log for warnings and errors

$\beta_{B2} < 90°$?

Design Understanding
Investigate parameter sensitivities, reduce complexity and generate best possible meta models

Design Improvement
Optimize design performance

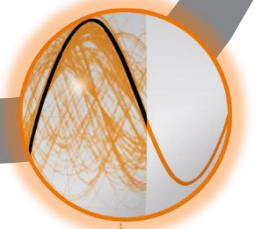




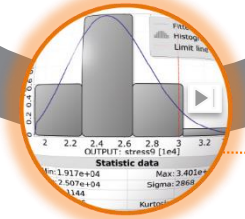
CAE-Data

Robust Design

Measurement Data

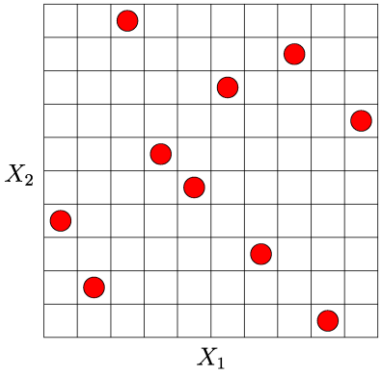


Model Calibration
Identify important model parameters for the best fit between simulation and measurement



Design Quality
Ensure design robustness and reliability

I Sensitivity analysis



Advanced Latin Hypercube Sampling

		Samples		
		100	200	300
Failed	CFturbo	15	32	46
	PumpLinx	1	3	9
Valid	samples	84	165	245
Reduced		74	139	233
CoP	Q	83.6 %	86.6 %	89.1%
	Δp_t	85.8 %	90.6 %	88.4 %
	P	91.5 %	92.9 %	94.0 %
	η	57.4 %	66.5 %	73.6 %

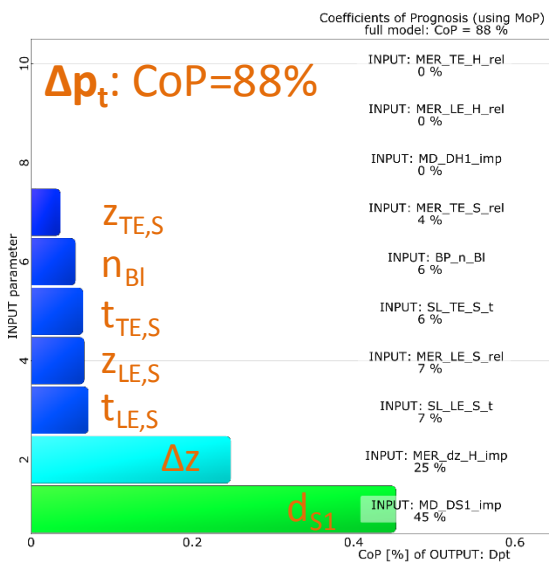
I Sensitivity analysis

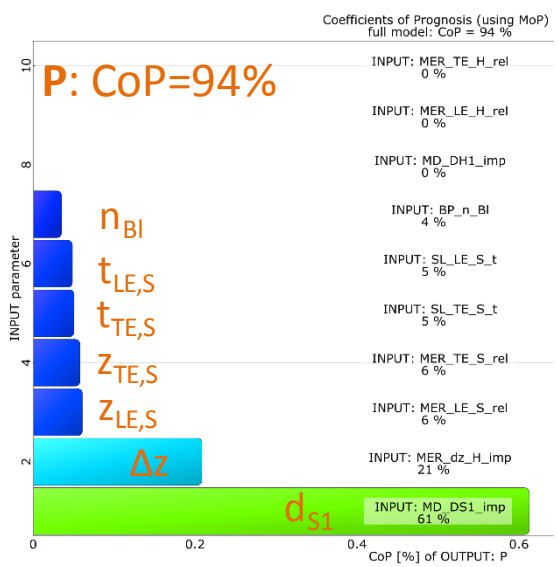
η hydraulic efficiency (objective)

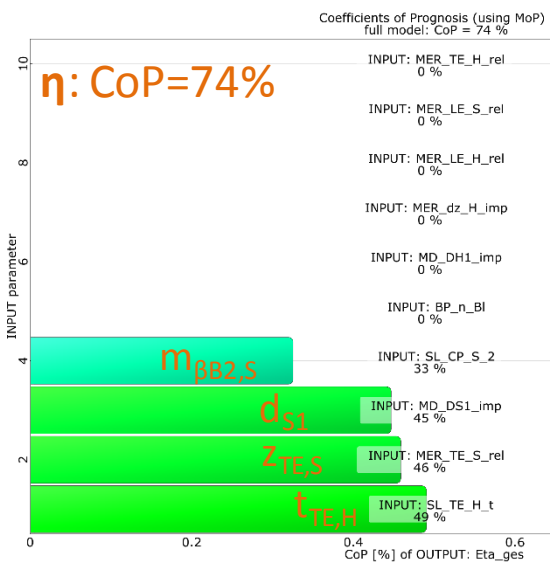
$$\eta = \frac{Q \cdot \Delta p_t}{P}$$

Q Flow rate
Δp_t Total pressure difference
P Power consumption

Reduced to 7 parameters







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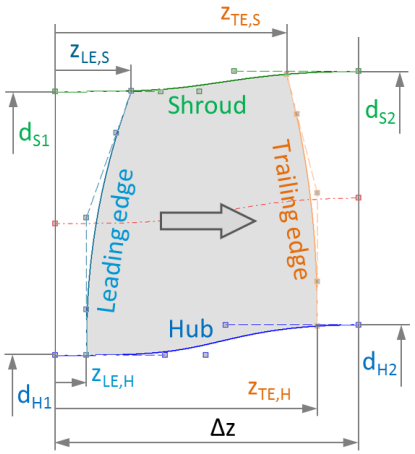
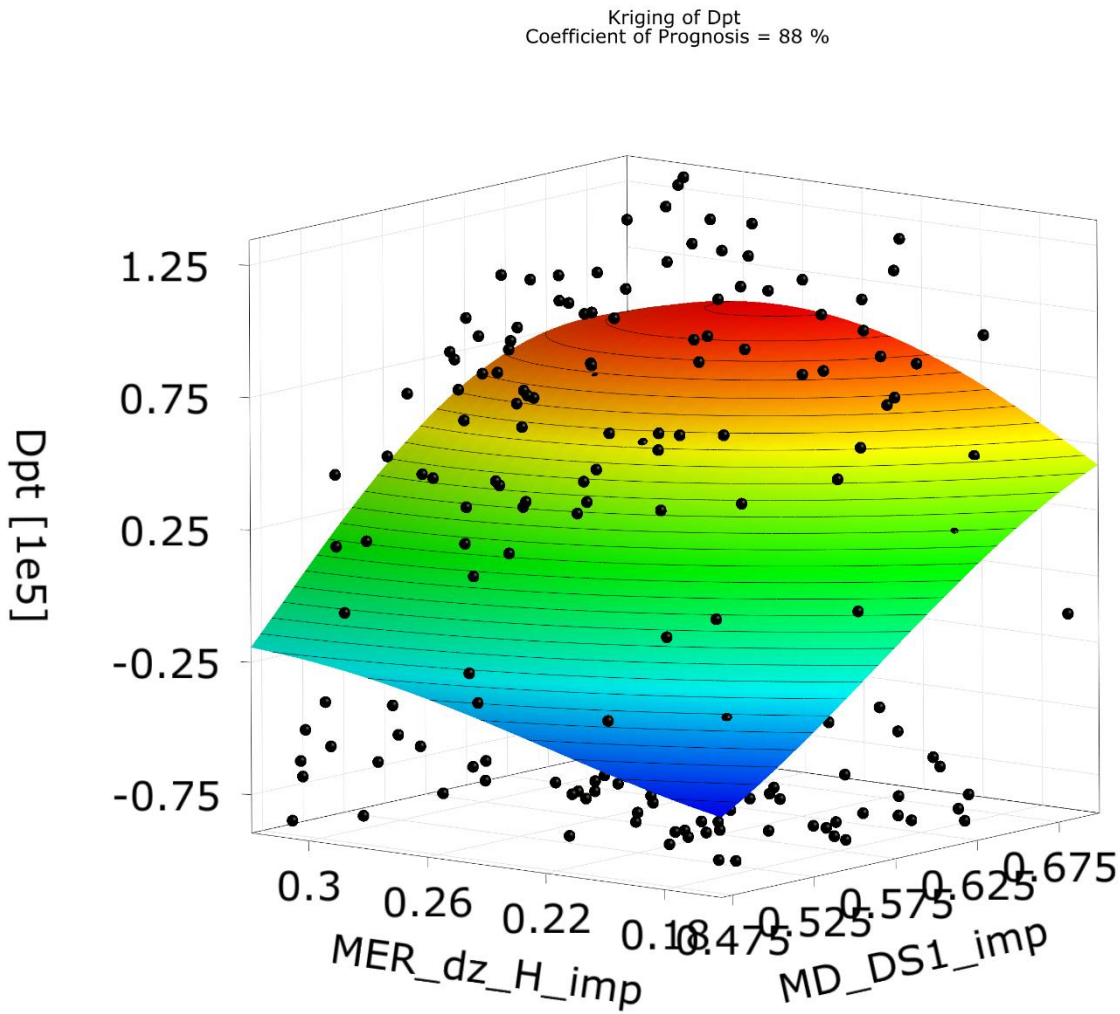
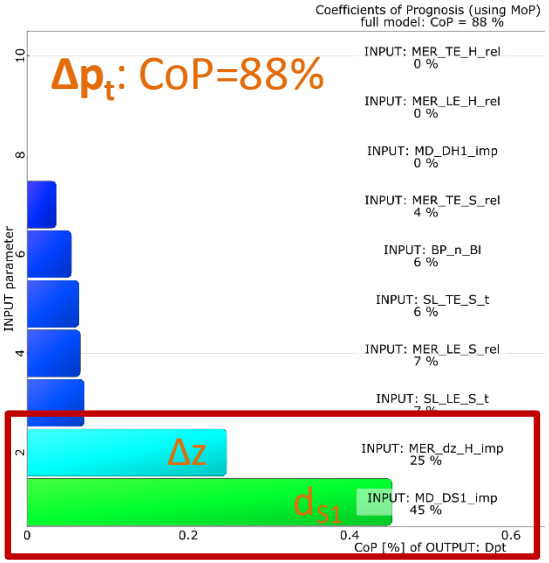


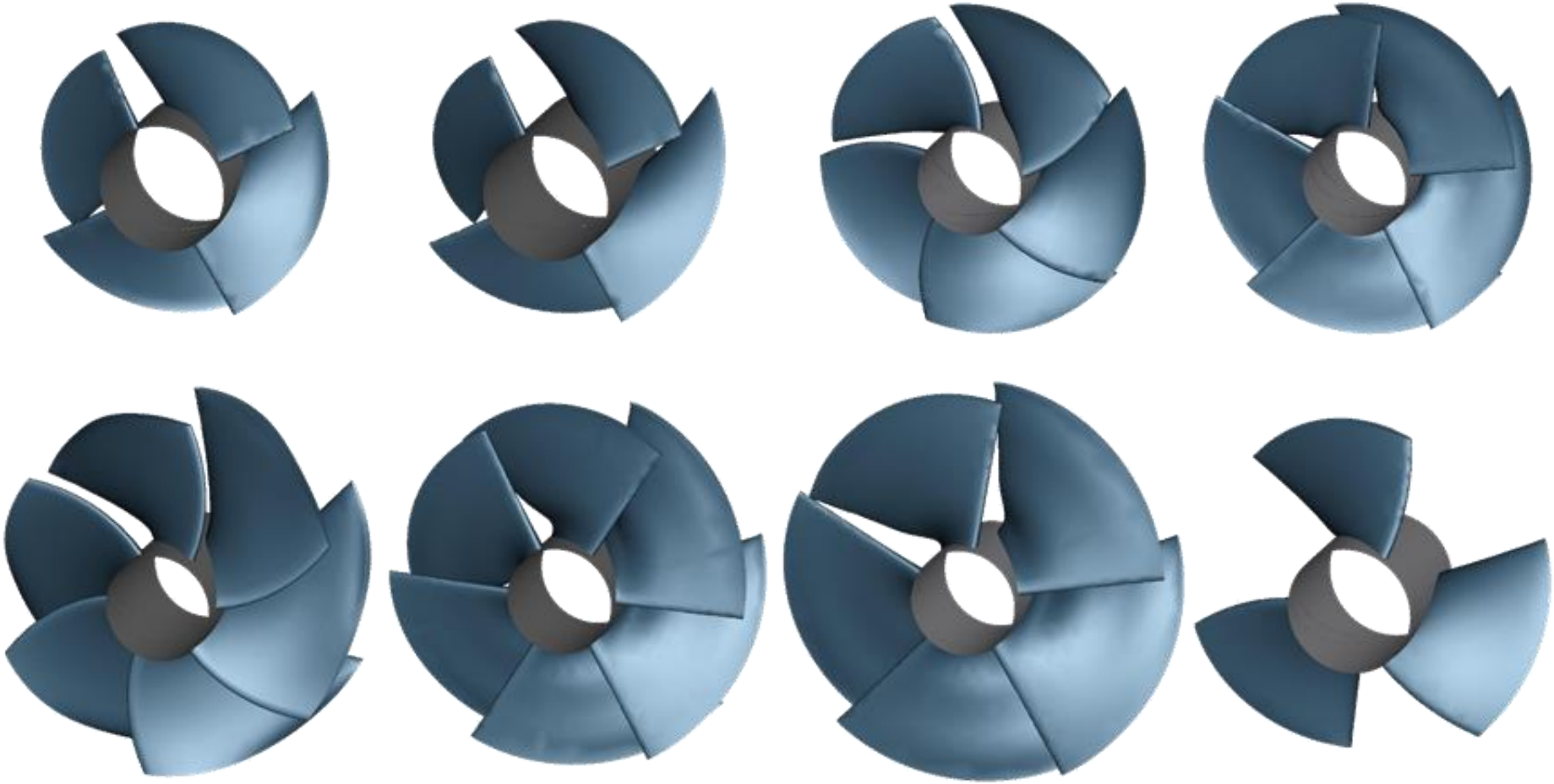


Response surface for

$\Delta p_t = f(d_{S1}, \Delta z)$



I Sensitivity analysis – Geometry examples



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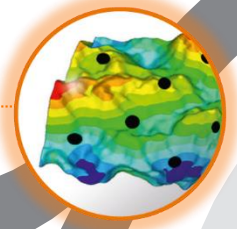
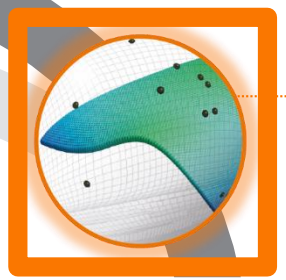
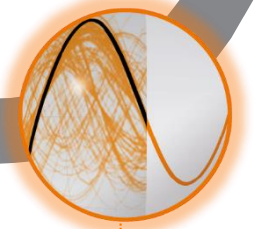




CAE-Data

Robust Design



Measurement Data

Model Calibration
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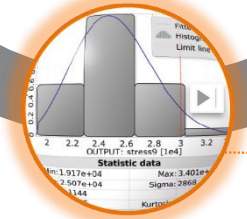


Design Quality
Ensure design robustness and reliability

I Optimization

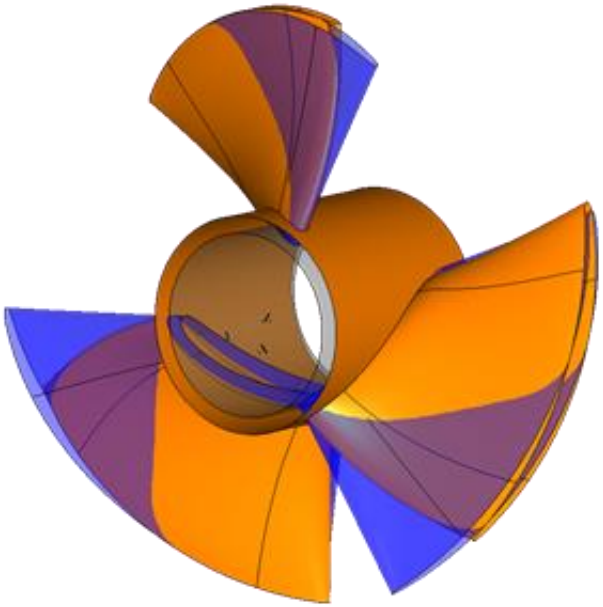
Algorithm	Samples	Simulation time	Simulation time/ sample	η
EA Evolutionary Algorithm	330	72.2 h (3.0 d)	13.1 min	69,9 % + 5.0 %
ARSM Adaptive Response Surface Method	540	126.3 h (5.3 d)	14.0 min	69,3 % + 4.4%

Desktop PC

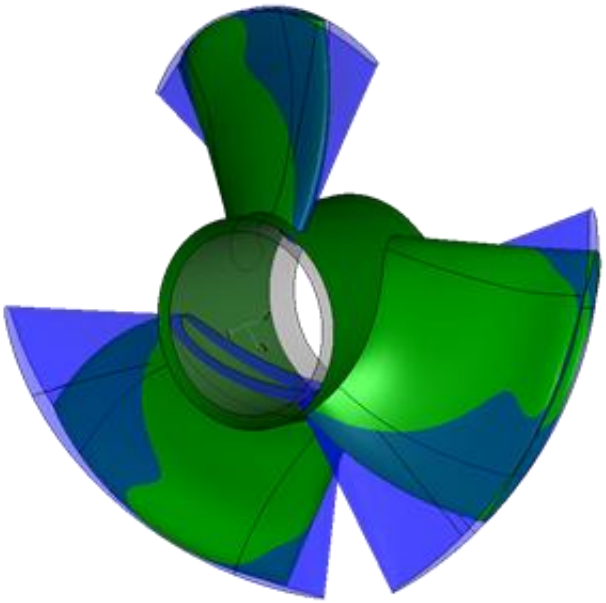
- 2 x Intel Xeon 3.07 GHz, 6 cores
- 64 GB RAM
- Max. 2 parallel simulation jobs

I Optimization

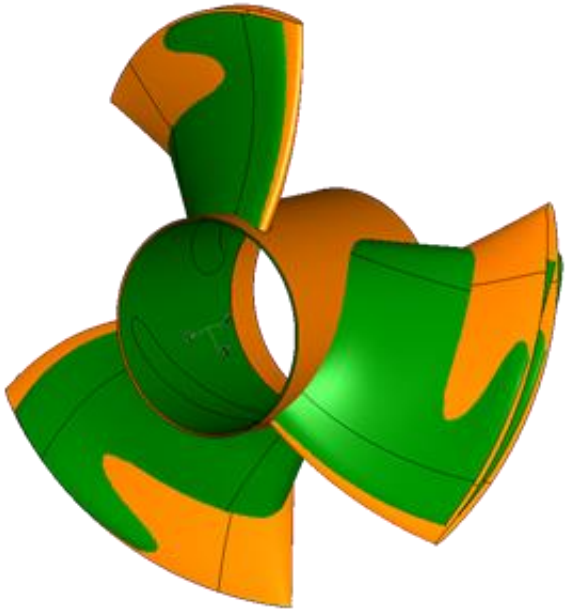
Initial
ARSM



Initial
EA



ARSM
EA



Summary

- Workflow CFturbo + PumpLinx + optiSLang successful set up and >80% successful designs in sensitivity analysis
- CFturbo initial design can be used as very reasonable starting point („pre-optimized") to save computation time
- CFturbo provides a well parametrized geometry that enables to work in a wide parameter range
- PumpLinx solver speed is beneficial for optimization and enables optimization on desktop PCs
- Threw the sensitivity analyses the imported parameters could be identified
- Number of parameters could be reduced to ~ 50% by sensitivity analysis for the direct optimization
- Efficiency could be improved by 5% compared to the reference design by using direct optimization

Outline

- Introduction into optiSLang and CFturbo

- I : Optimization of an axial pump (M. Korfanty, CFturbo GmbH)
  - Aim of analysis
  - CAE Workflow
  - Sensitivity analysis
  - Optimization
  - Summary

- **II : Performance map analysis of a radial compressor** (M. Wagner, Dynardo GmbH)
  - Aim of analysis
  - CAE Workflow
  - Sensitivity analysis
  - Optimization on MOP
  - Summary

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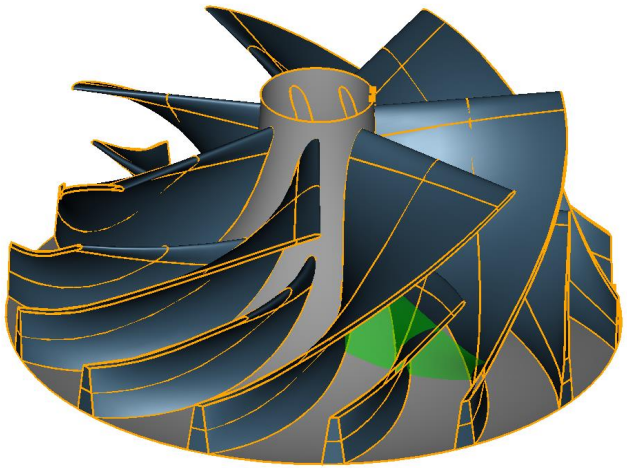
II Aim of analysis



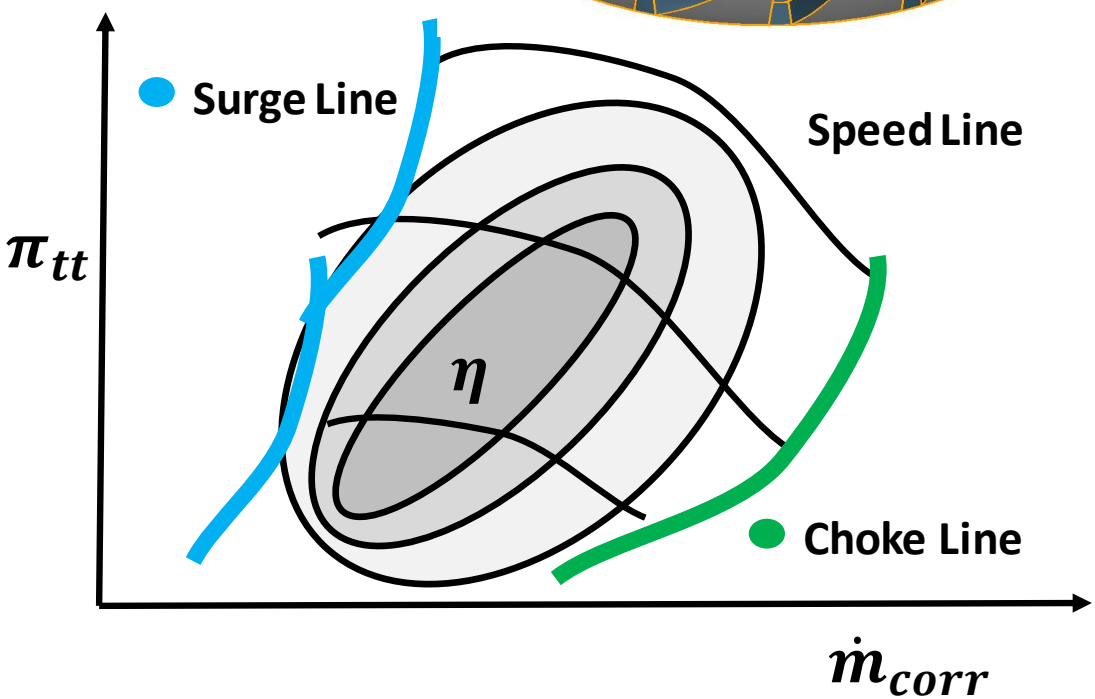
Performance indicators for characterizing turbochargers:

- Pressure ratio $\pi_{tt} = \frac{p_{t\,2}}{p_{t\,1}}$
- Isentropic efficiency

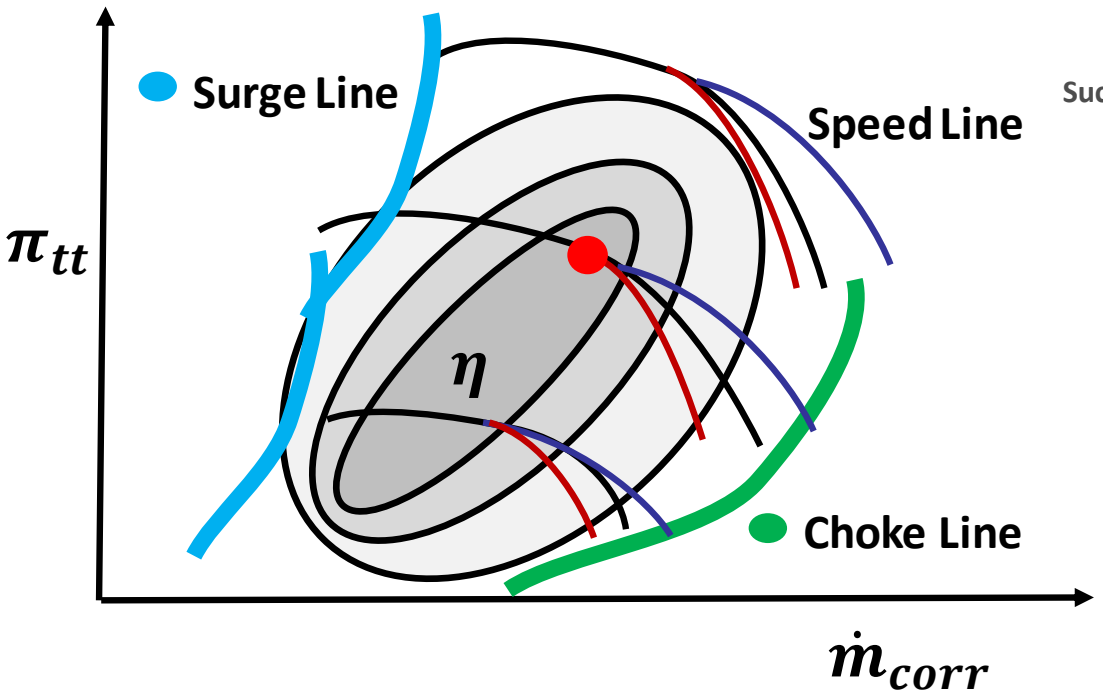
$$\eta_s = \frac{\left[\left(\frac{p_{t\,2}}{pt_{\,1}}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]}{\left(\frac{T_{t\,2}}{T_{t\,1}} - 1\right)}$$

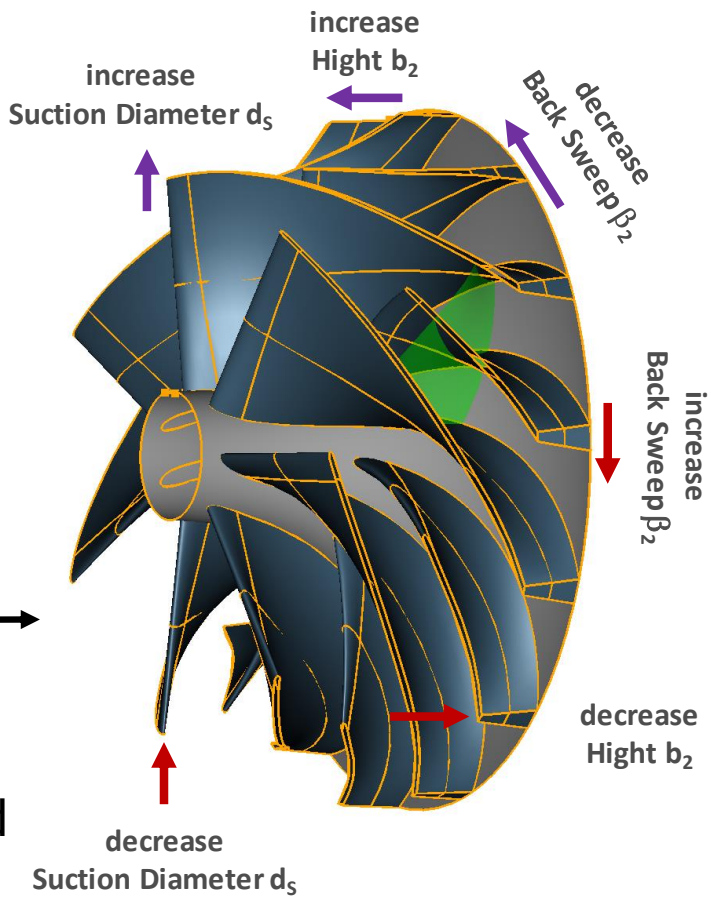
- polytropic efficiency

$$\eta_p = \frac{\frac{\kappa-1}{\kappa}\ln\left(\frac{p_{t\,2}}{p_{t\,1}}\right)}{\ln\left(\frac{T_{t\,2}}{Tt_{\,1}}\right)}$$



II Aim of analyzes





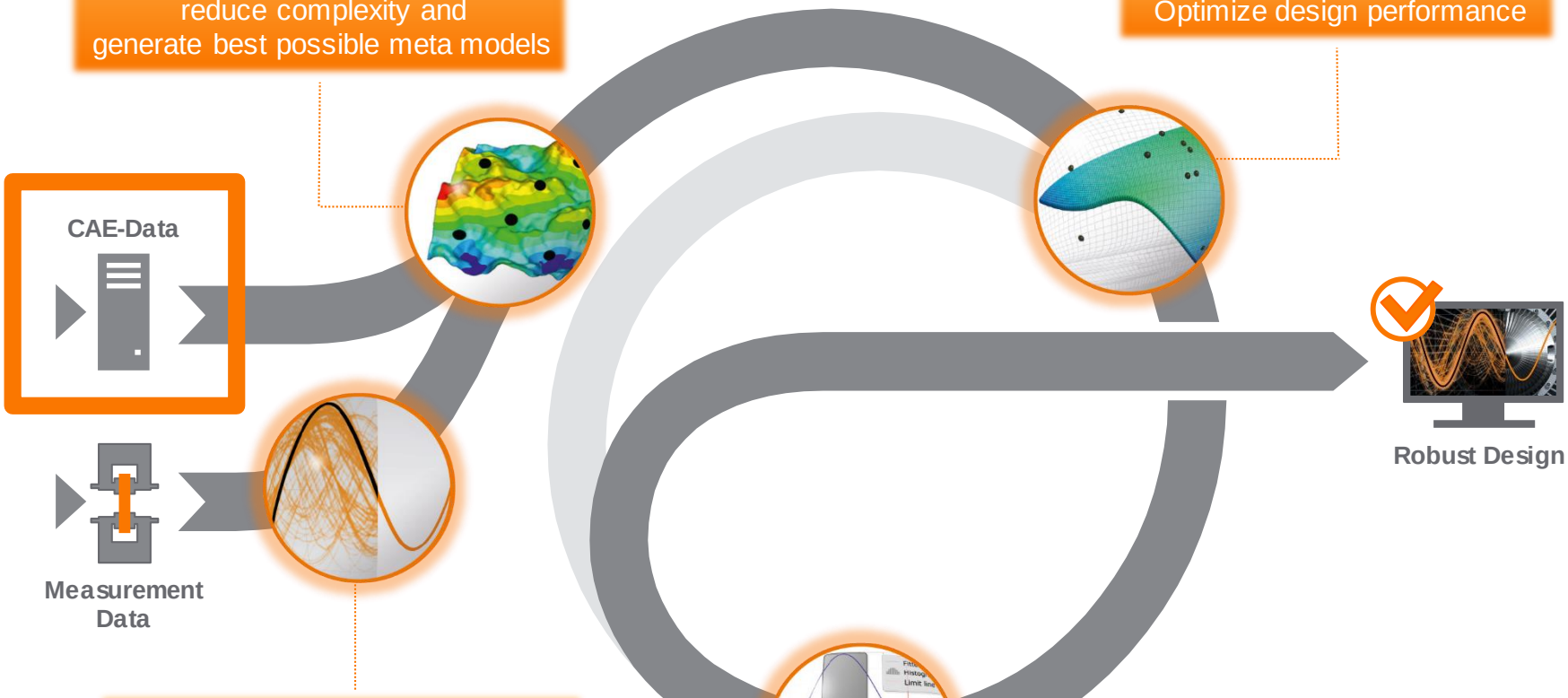
- Fixed reference points (choke, optimum, surge) will not be conserved with parameter changes!
- How to analyze and compare maps?

Design Understanding

Investigate parameter sensitivities, reduce complexity and generate best possible meta models

Design Improvement

Optimize design performance



Model Calibration

Identify important model parameters for the best fit between simulation and measurement

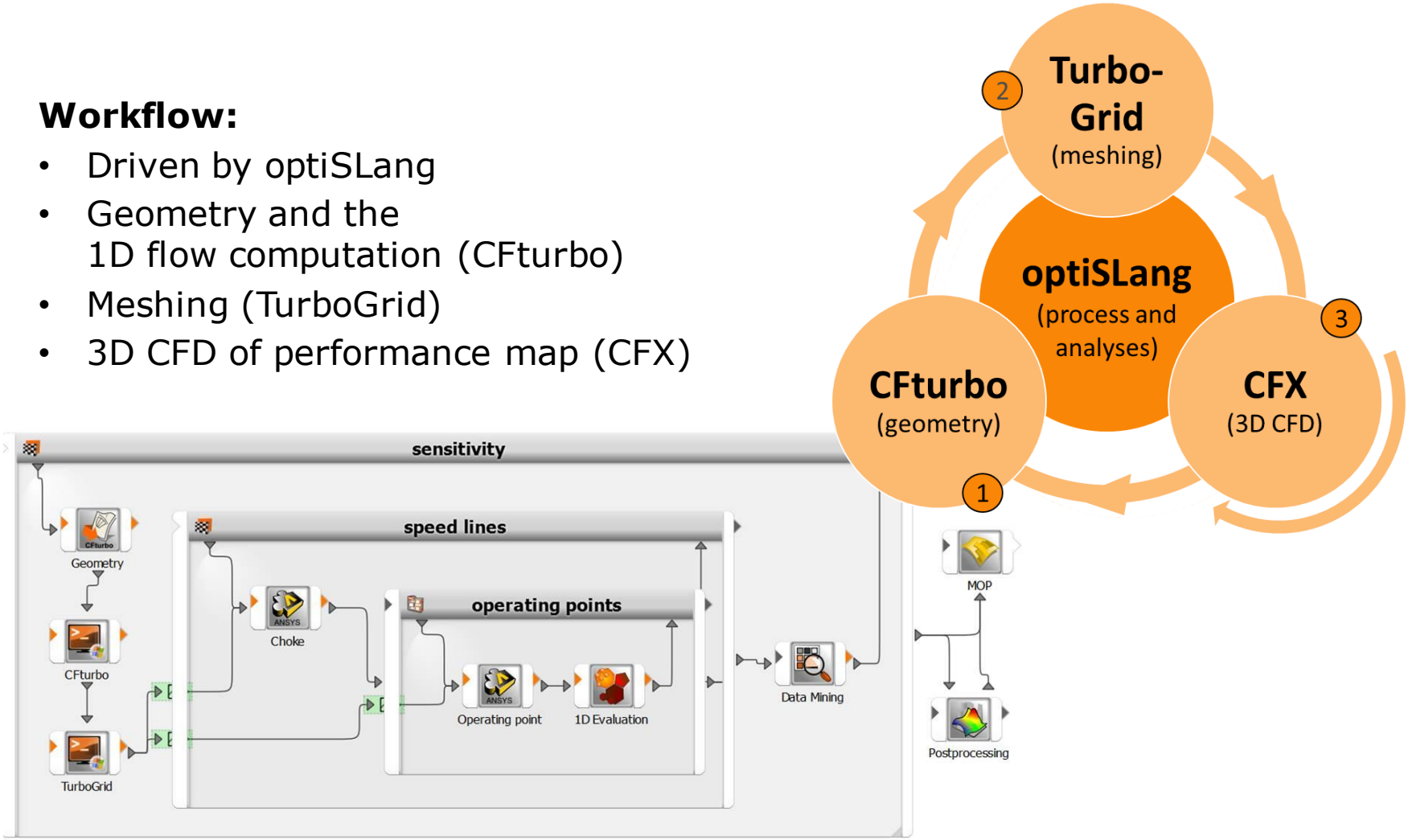
Design Quality

Ensure design robustness and reliability

II CAE Workflow

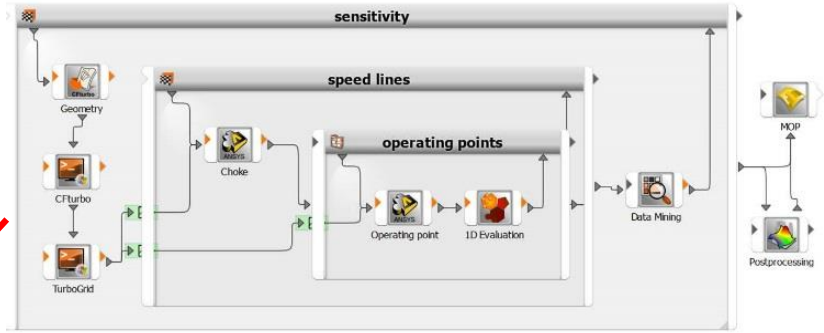
Workflow:

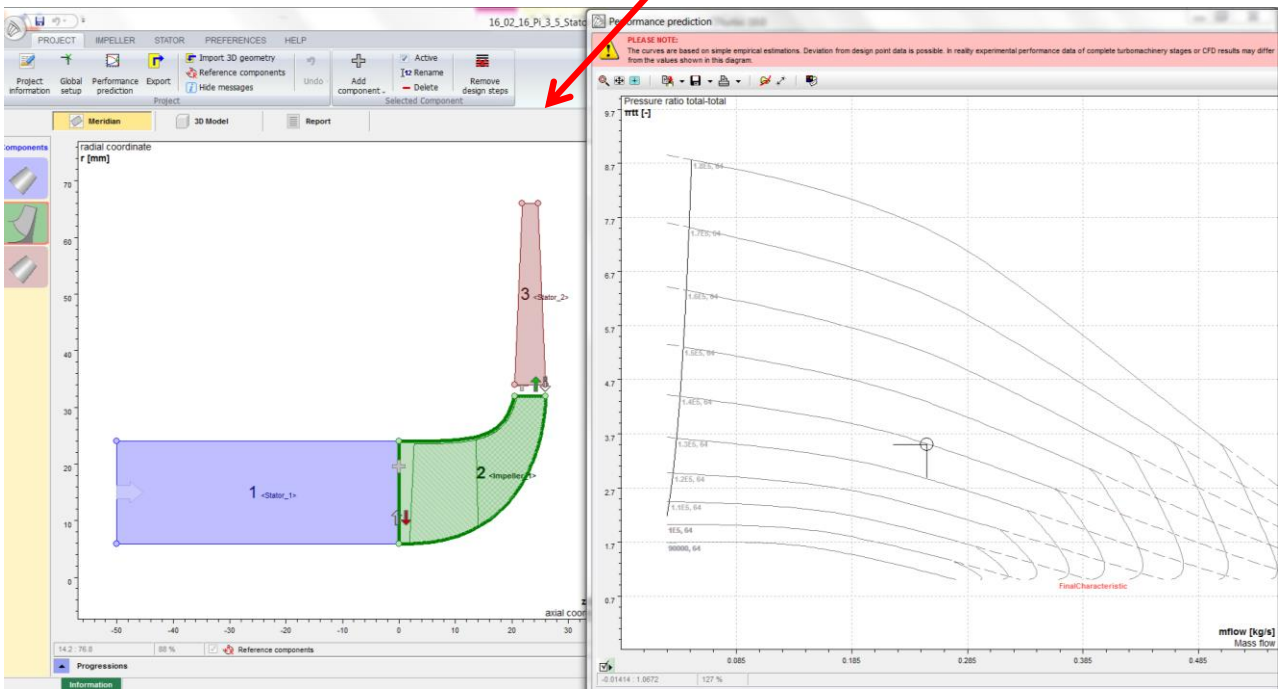
- Driven by optiSLang
- Geometry and the
  1D flow computation (CFturbo)
- Meshing (TurboGrid)
- 3D CFD of performance map (CFX)



II CAE Workflow

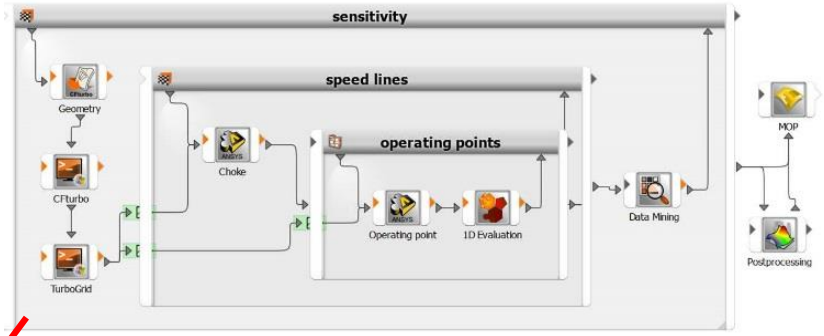
- Geometry parameters are determined to generate a 3D geometry
- CFturbo allows geometry variations in a large design space

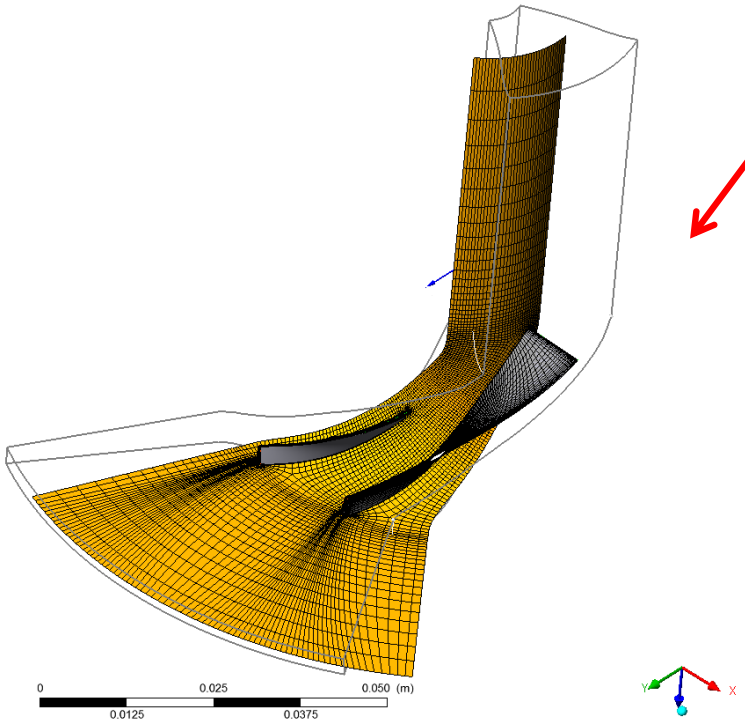


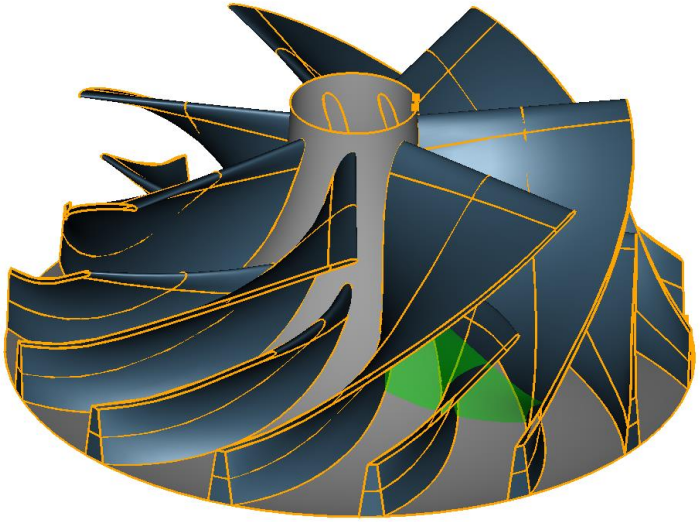


II CAE Workflow

- 3D Geometry (right)
- Meshing of periodic segment with TurboGrid (left)

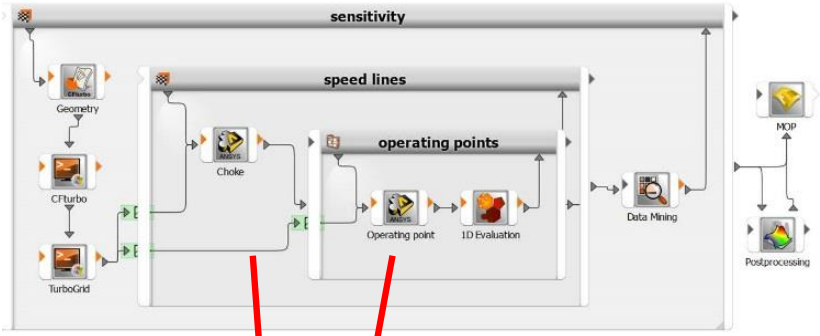


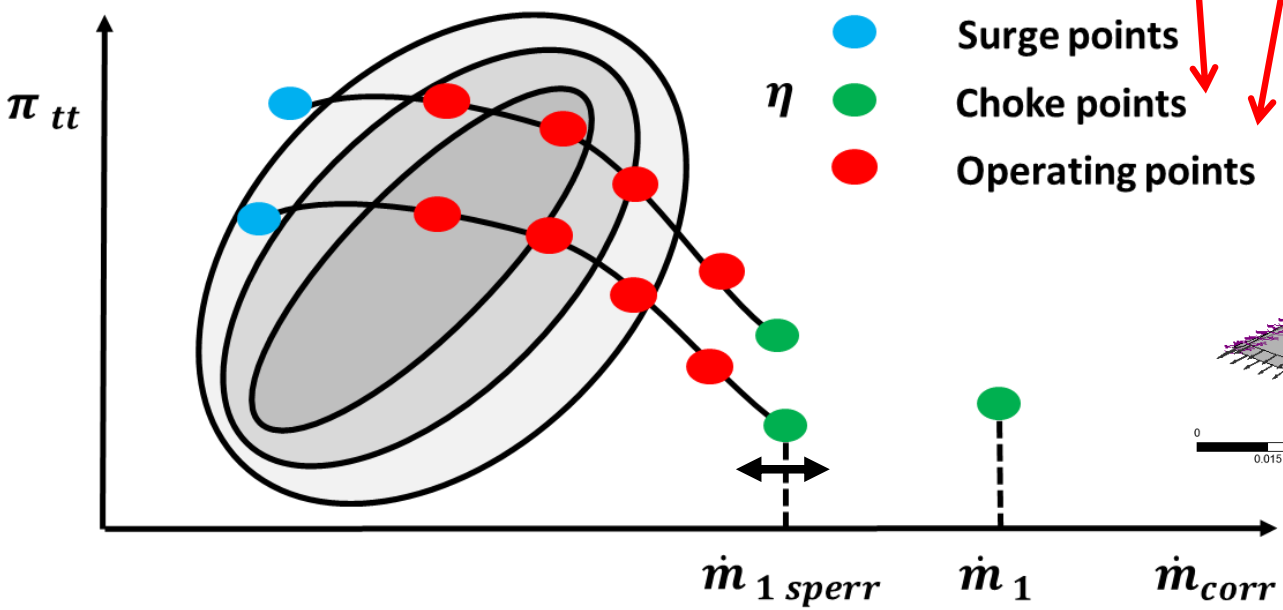


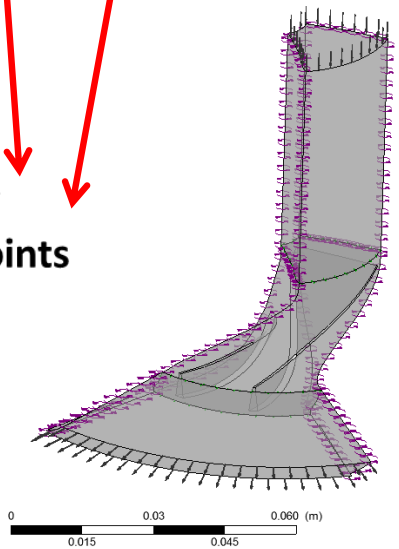


II CAE Workflow

1. Calculate "choke point"
   → choke mass flow
   (Dimensional analyses)
2. Reduce mass flow
   → "operating points"
3. Stop at estimated surge (user defined limit)





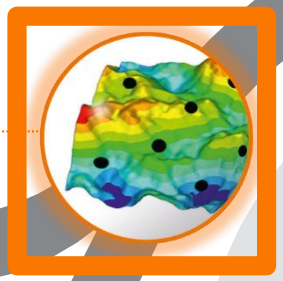


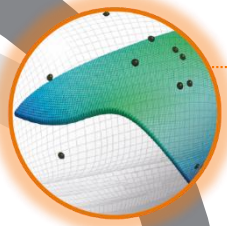
Design Understanding

Investigate parameter sensitivities, reduce complexity and generate best possible meta models

Design Improvement

Optimize design performance

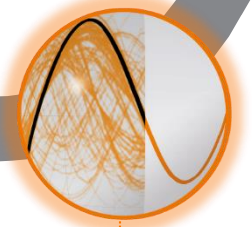




CAE-Data

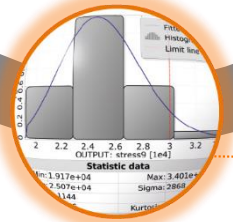
Robust Design

Measurement Data



Model Calibration

Identify important model parameters for the best fit between simulation and measurement



Design Quality

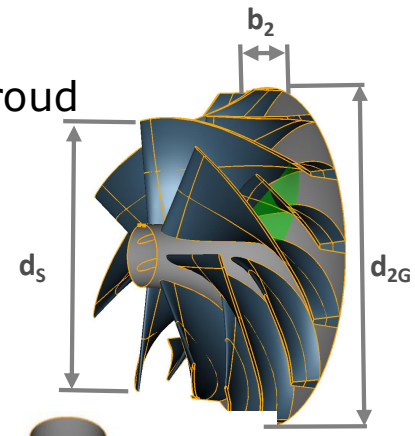
Ensure design robustness and reliability

II Sensitivity analysis Parametrization

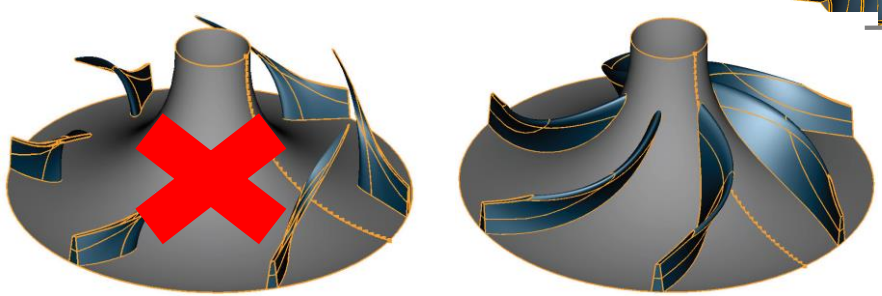
Parameters that have been used:

- global parameters: d_{2G}=konst., b_2, d_S
- leading edge of main and splitter blade
- blade angle $ß_1$, $ß_2$
  ($ß_2$: hub dep. on shroud)
- Bezier curves hub and shroud
- number of Blades
- blade mean lines
- wrap angle

Total 31 free Parameter



	Name	Reference value	Operation	Resolution	Range		Range plot
1	nSector	6	_Impeller_1_1.nBl/2				
2	X_S2	0.298315	X_S2_Anstieg*_Impeller_1_1.GeoSplitLe...				
3	warp_angle_delta	0		Continuous	0	0.2	
4	X_S	0.35	max(X_S1,X_S2)				
5	X_S_Wertebereich	0.5		Continuous	0	1	
6	_Impeller_1_1.nBl	12		Ordinal discrete (by index)	8; 10; 12; 14; 16; 18		
7	_Impeller_1_1.GeoLeadingEdge.u_Hub	0.0446449		Continuous	0.025	0.15	
8	dS_delta	0.75		Continuous	0.5	0.8	
9	_Impeller_1_1.Version_1.dS	0.048	_Impeller_1_1.Version_1.d2*dS_delta				
10	_Impeller_1_1.MainBlades.0.Point3.x	1.29822	_Impeller_1_1.MainBlades.2.Point3.x + warp_angle_delta				
11	_Impeller_1_1.Version_1.b2	0.0055		Continuous	0.005	0.006	
12	_Impeller_1_1.GeoLeadingEdge.u_Shroud	0.107324		Continuous	0.025	0.26	
13	_Impeller_1_1.MainBlades.2.Point3.x	1.29822		Continuous	1.09	1.48	
14	_Impeller_1_1.GeoSplitLeadingEdge.u_Hub	0.348315		Continuous	0.2	0.75	
15	_Impeller_1_1.GeoSplitLeadingEdge.u_Shr...	0.525	X_S_Wertebereich*(0.7-X_S)+X_S				
16	_Impeller_1_1.GeoHub.0.Rel1.x	0.299158		Continuous	0.15	0.45	
17	_Impeller_1_1.GeoHub.0.Rel1.y	-1.03032e-09		Continuous	-0.07	0.07	
18	_Impeller_1_1.GeoHub.0.Rel2.x	1		Continuous	0.85	1.1	
19	_Impeller_1_1.GeoHub.0.Rel2.y	2.85369e-09		Continuous	-0.15	0.15	
20	_Impeller_1_1.GeoHub.0.Rel3.x	1		Continuous	0.96	1.05	
21	_Impeller_1_1.GeoHub.0.Rel3.y	0.950027		Continuous	0.8	0.97	
22	_Impeller_1_1.GeoShroud.0.Rel1.x	0.627744		Continuous	0.48	0.78	



e.g. Position of leading edge at splitter

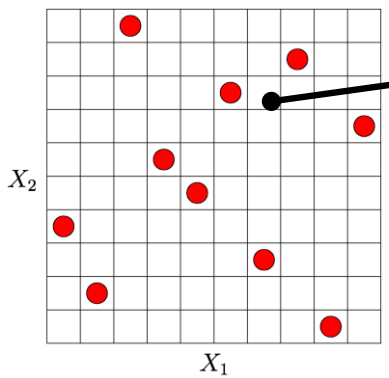
II Sensitivity analysis Methodology

Sensitivity analysis scans the design space and evaluates the variance of the inputs- (e.g. Geometry) output parameters (e.g. pressure ratio)

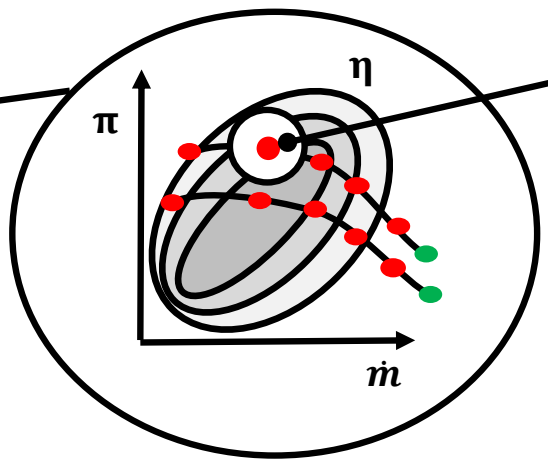
1) Design of experiments within the design space of the sensitivity analysis and calculate the Designs,

2) Usage of regression methods for setting Meta-Models e.g. pressure ratio and

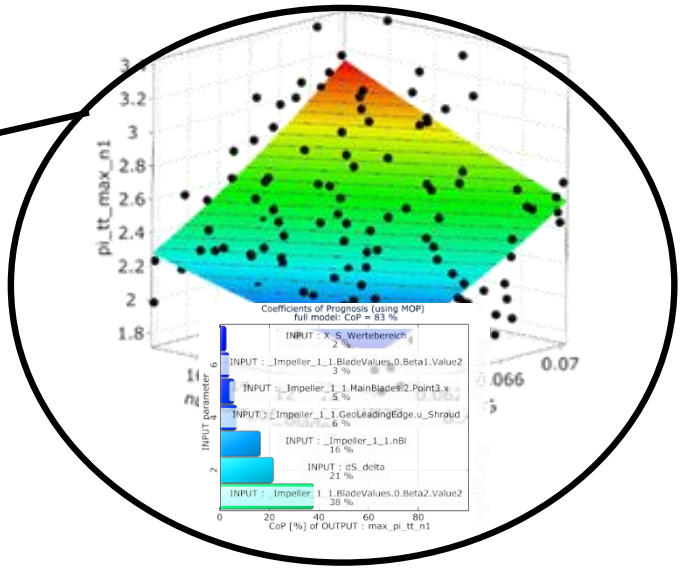
3) Evaluate important parameters



Advanced Latin Hypercube Sampling



One Design represents one performance map



MOP for one operating point

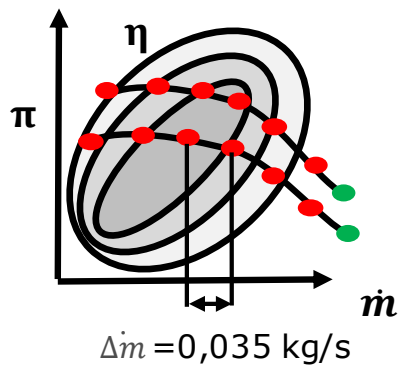
II Sensitivity analyzes
Results overview

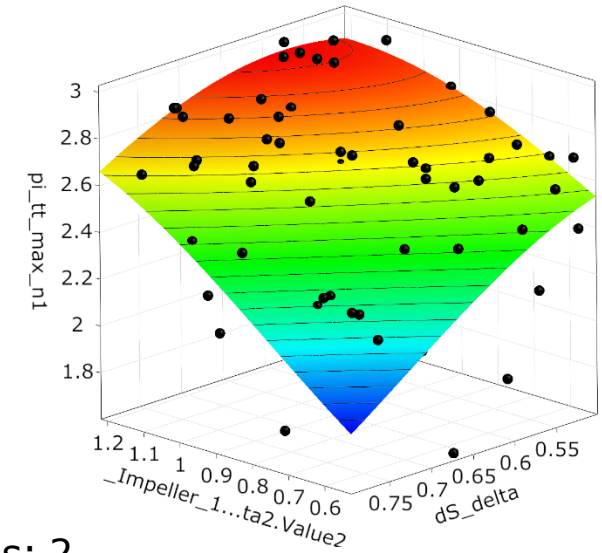
sensitivity study of performance maps

- 88% successful design points
  - 1% no geometry generation
  - 5% failed meshing
  - 6% problems with CFD Solver

Generation of response surfaces

- Approximation accuracy is good for choke and $\pi_{tt\ max\ n1}$
- Dissatisfying quality e.g. for $\eta_{p\ max}$
- Increase number of Designs/ speed line for better COP!



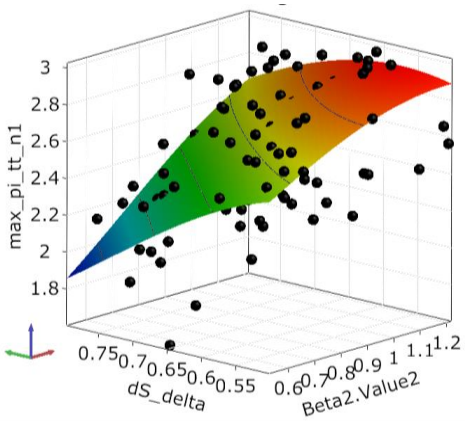


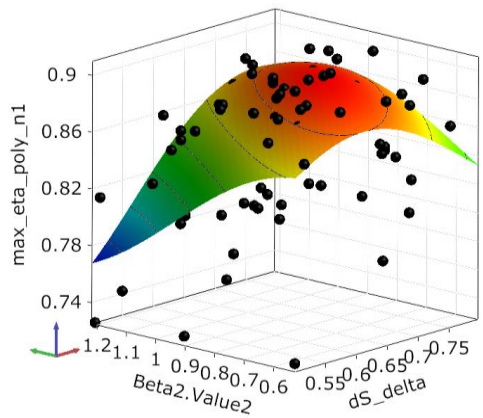
Number of speed lines: 2

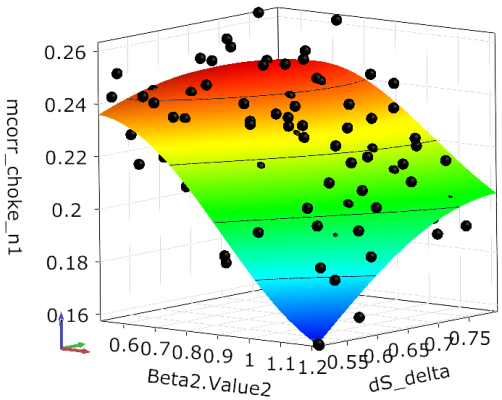
Max. number of operating points/ speed line: 6

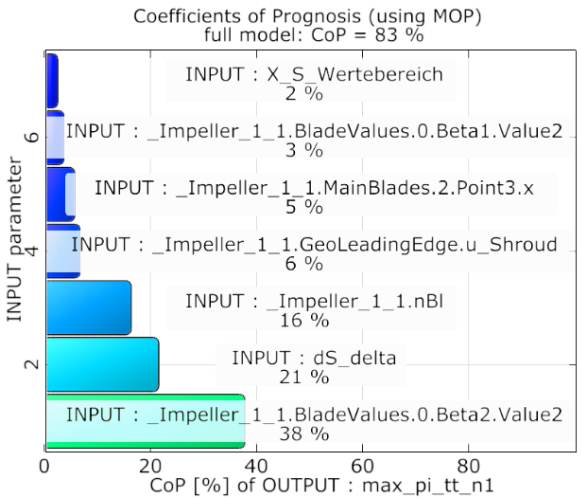
Meta-modell	$n_1 = 120000\ [1/min]$			$n_2 = 150000\ [1/min]$		
	$\pi_{tt\ max}$	$\eta_{p\ max}$	*choke massflow*	$\pi_{tt\ max}$	$\eta_{p\ max}$	*choke massflow*
CoP [%]	83	45	91	45	48	91

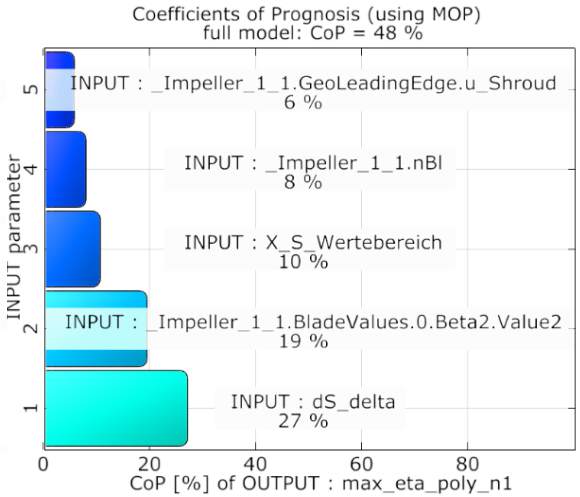
II Sensitivity analysis
Meta-Model, Results for $n1$=120000 [$1/min$]

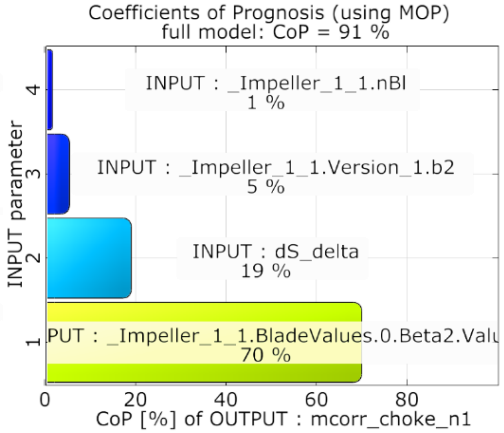










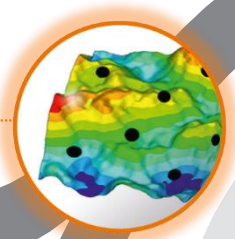


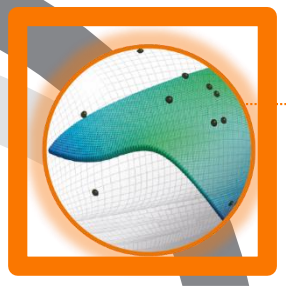
Design Understanding

Investigate parameter sensitivities, reduce complexity and generate best possible meta models

Design Improvement

Optimize design performance

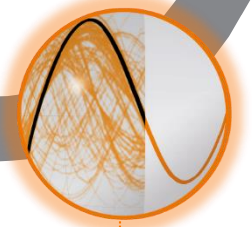




CAE-Data

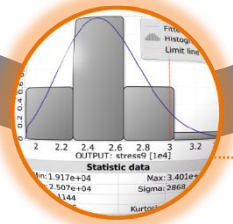
Robust Design

Measurement Data



Model Calibration

Identify important model parameters for the best fit between simulation and measurement

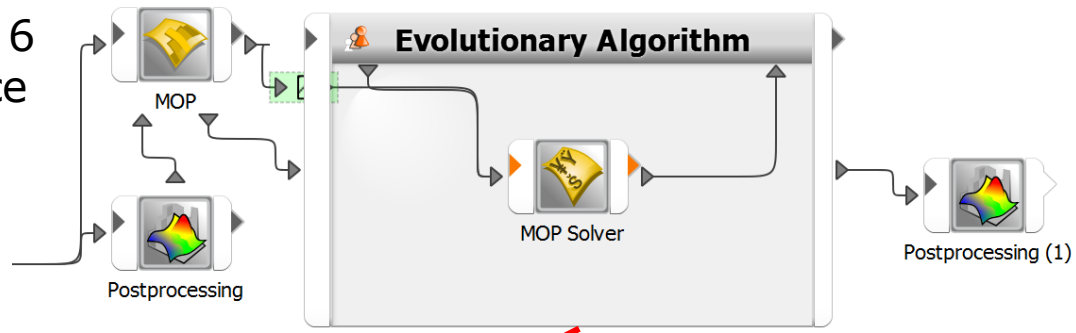


Design Quality

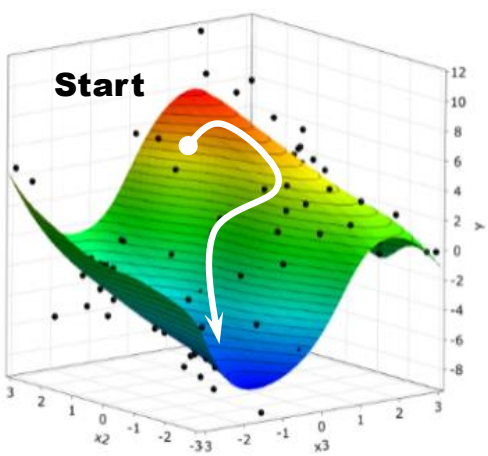
Ensure design robustness and reliability

II Optimization on MOP Methodology

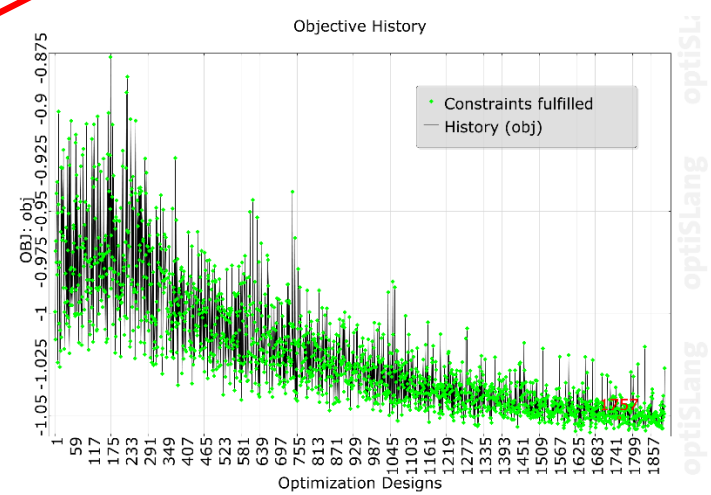
- Objective function includes 6 values for each performance map, optimization on 6 Response Surfaces (MOP)
- Algorithm used: global evolutionary algorithm
- Validating best design with real solver call



$$ZF = \frac{1}{3n}\sum_{i=1}^{n}\left(\frac{\dot{m}_{sperr,i}}{\dot{m}_{ref,i}} + \frac{\eta_{p\,max,i}}{\eta_{p\,max\,ref,i}} + \frac{\pi_{tt\,max,i}}{\pi_{tt\,max\,ref,i}}\right)$$

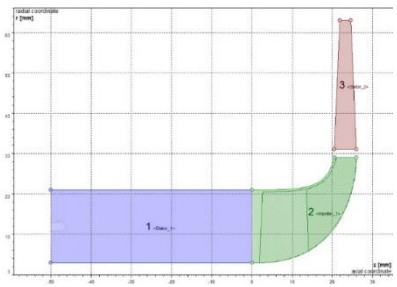


Optimization using MOP

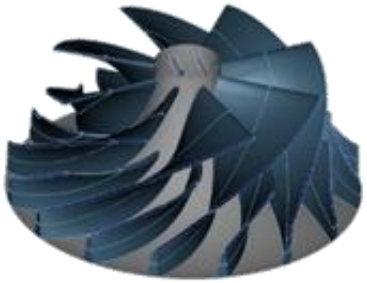


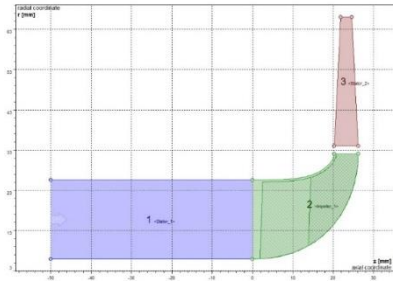
II Optimization on MOP
Result comparison

Reference Design

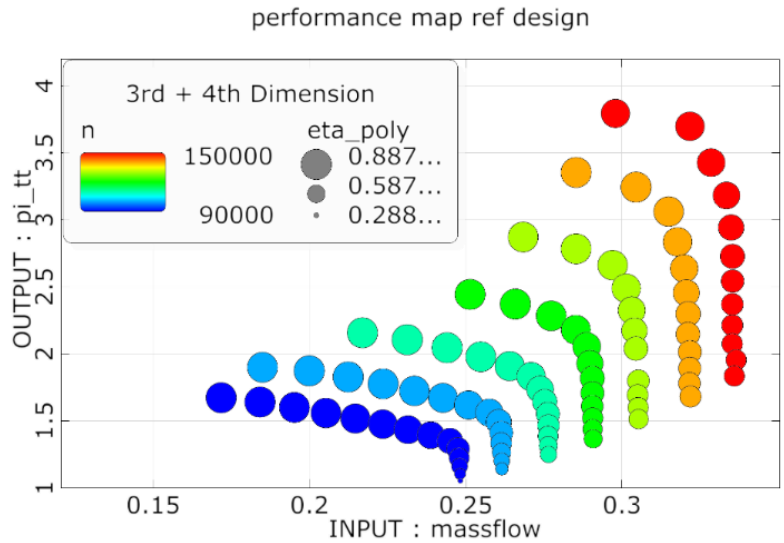


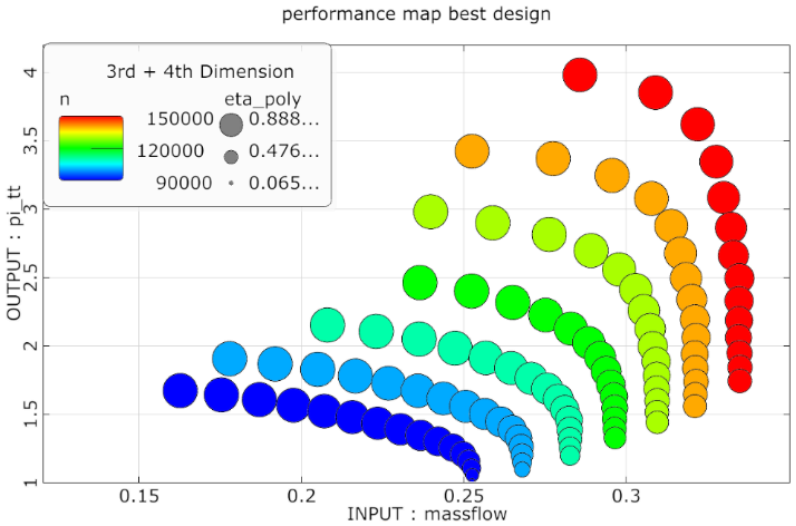
Optimization on MOP





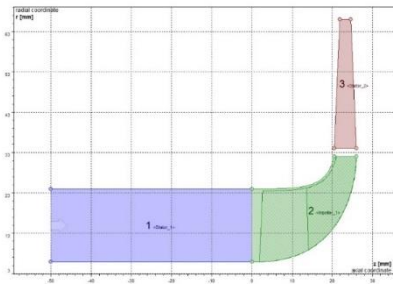
	$n_1 = 120000\ [1/min]$			$n_2 = 150000\ [1/min]$		
	$\pi_{tt\,max}$	$\eta_{p\,max}$	$choke\ massflow$	$\pi_{tt\,max}$	$\eta_{p\,max}$	$choke\ massflow$
ref	2,44	0,897	0,228	3,79	0,868	0,208
opt	2,52	0,885	0,251	4,02	0,862	0,230



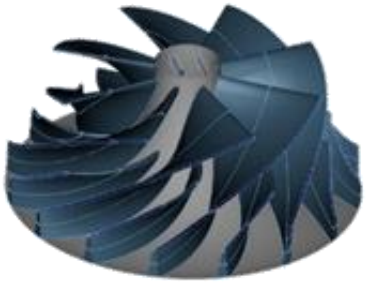


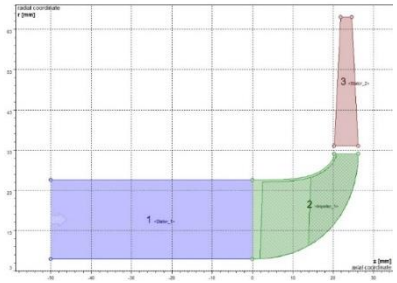
II Optimization on MOP
Result comparison

Reference Design



Optimization on MOP





	$n_1 = 120000\ [1/min]$			$n_2 = 150000\ [1/min]$		
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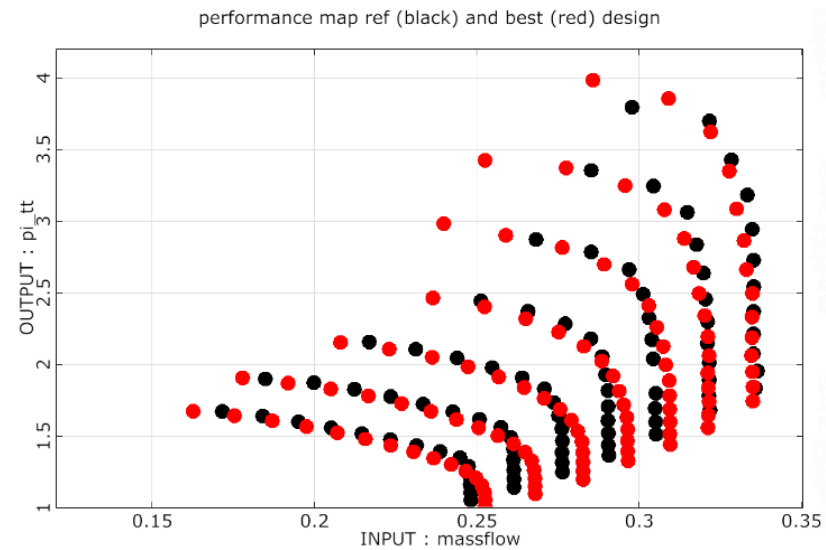
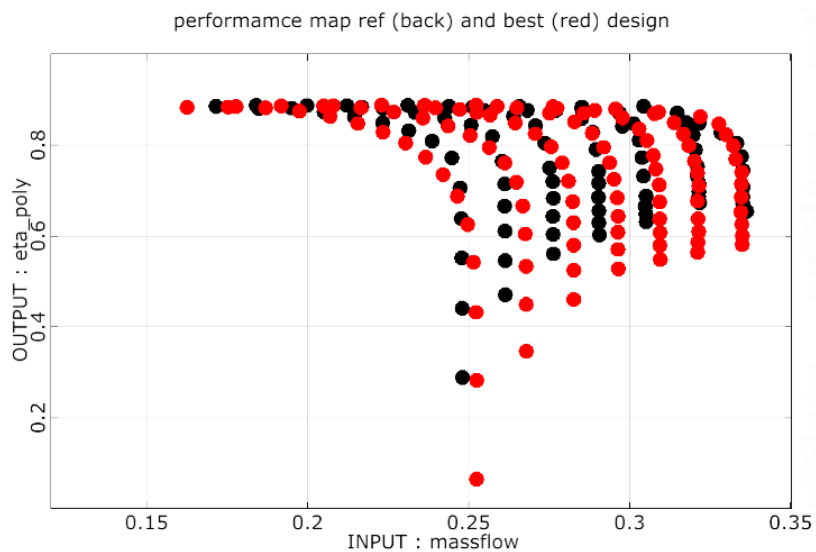
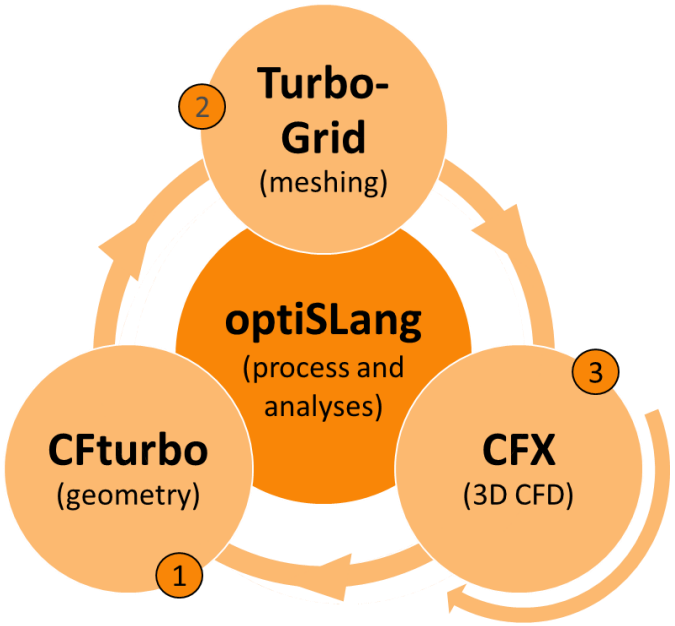


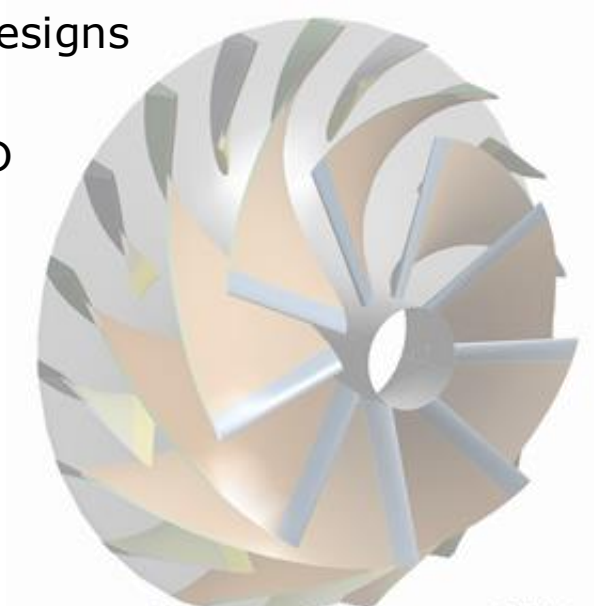


II Summary

Methodology of adaptive analysis of performance maps:

- ✓ Automation of an adaptive workflow
- ✓ In Sensitivity successful applied for ~90% of the designs
- ✓ Optimization on MOP successful applied
- • Improves method for performance maps in 3D-CFD





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