Design and Development of centrifugal pumps
with the latest techniques used to optimize the performance

Dr. Gero Kreuzfeld

CFturbo

ICOMP 2023 - International Conference on Pumps and Motors

Topics

4 Optimization project examples

1 Introduction CFturbo GmbH

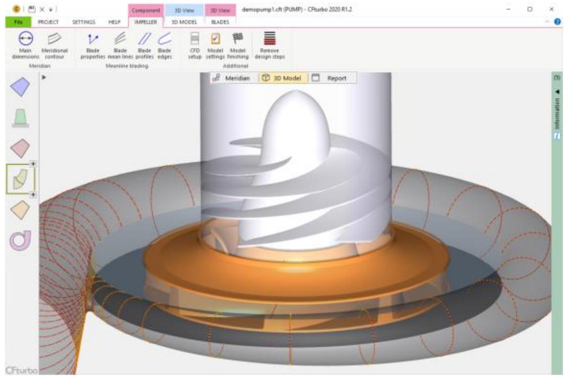
CFturbo GmbH Dresden (Germany)
est. 2008

CFturbo

CFturbo, Inc. New York (USA)
est. 2017

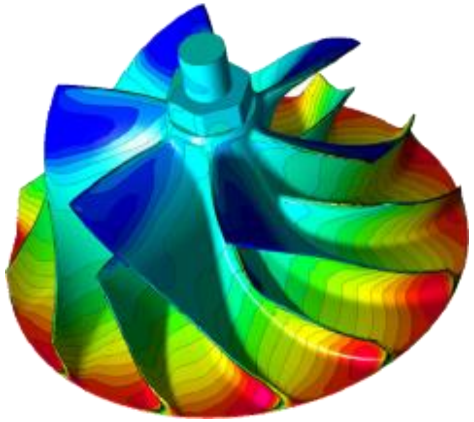
Design Software

- Turbomachinery Design Software
- Automated workflows
- Custom development



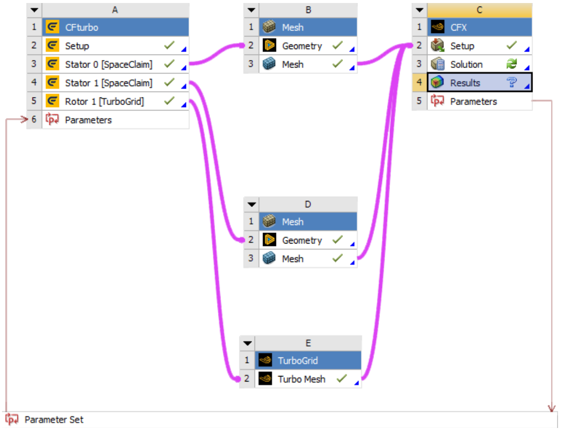
Engineering Services

- CFD/FEA-Simulation
- Digital Design Space Exploration
- Optimization



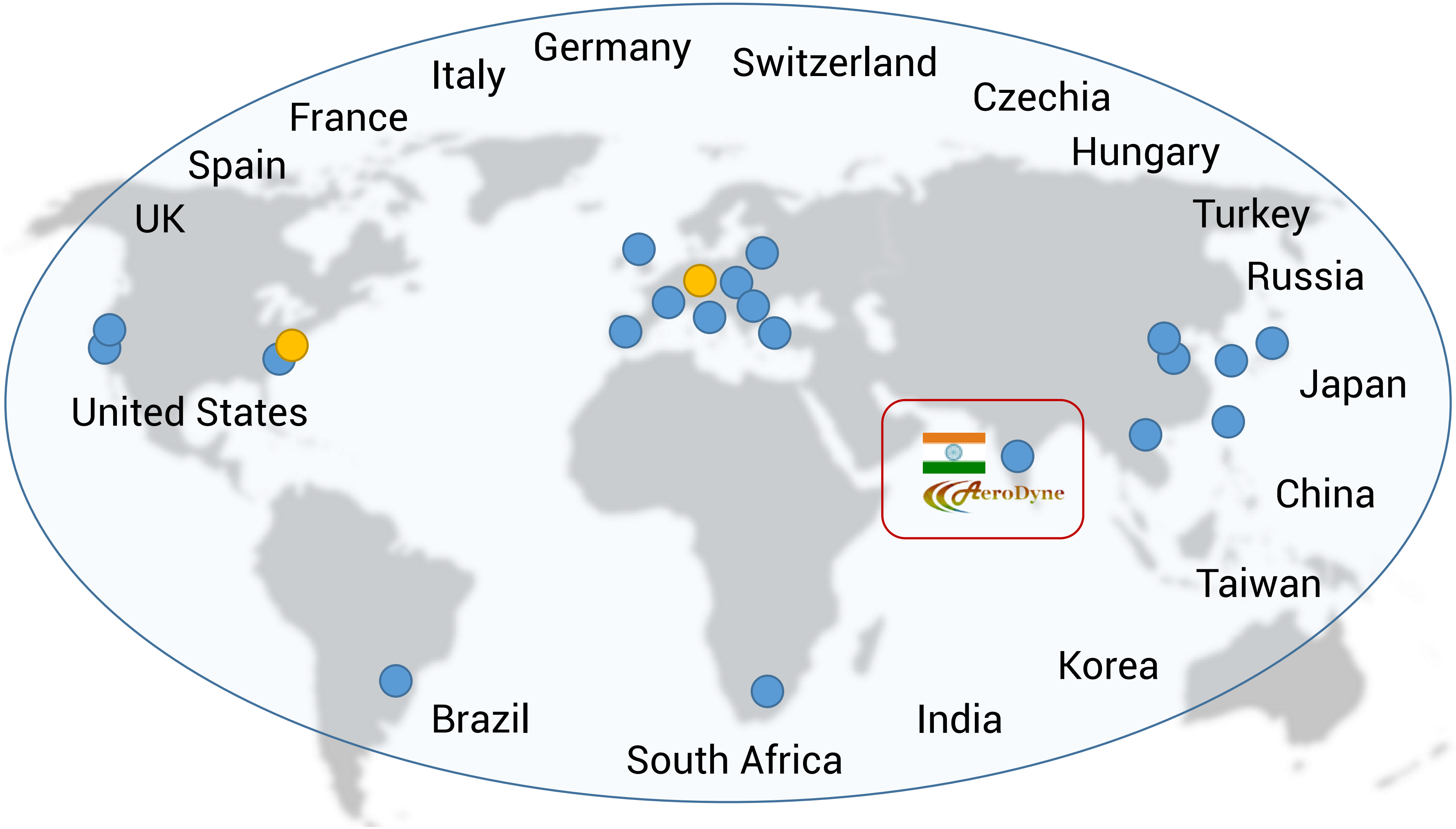
Workflow Development

- Automated workflows
- Simulation
- Design Exploration
- Optimization



1 Introduction CFturbo GmbH

● CFturbo Offices ● CFturbo Distributors



1 Introduction CFturbo GmbH

Various Industries • Large Corporations and SMB • Experts and Beginners

Renewables

Water & Wastewater

Oil & Gas

Chemical & Process Industry

Datacenters

Food

Aerospace

MedTech

Automotive

Marine

Appliances

HVAC

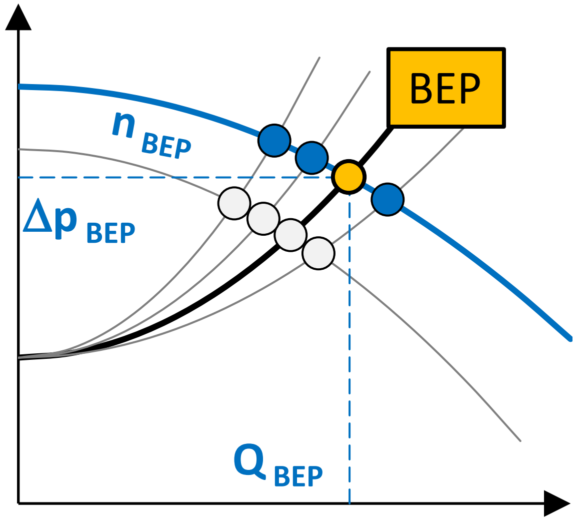
IT-Hardware

Topics

4 Optimization project examples

2 Design of centrifugal pumps with CFturbo

Design methodology



Define design point
Best Efficiency Point (BEP)

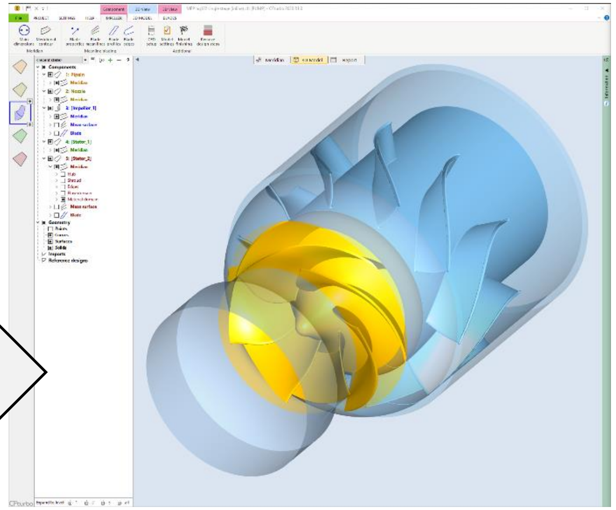
Volume/ mass flow rate
Head/ total pressure difference
Rotational speed
Fluid properties
Inlet conditions

Fundamental equations
Bernoulli-, Euler equation,
Mass-, Momentum-,
Energy conservation, …

CFturbo

Empirical correlations
Using publicly available knowledge, or own proprietary data

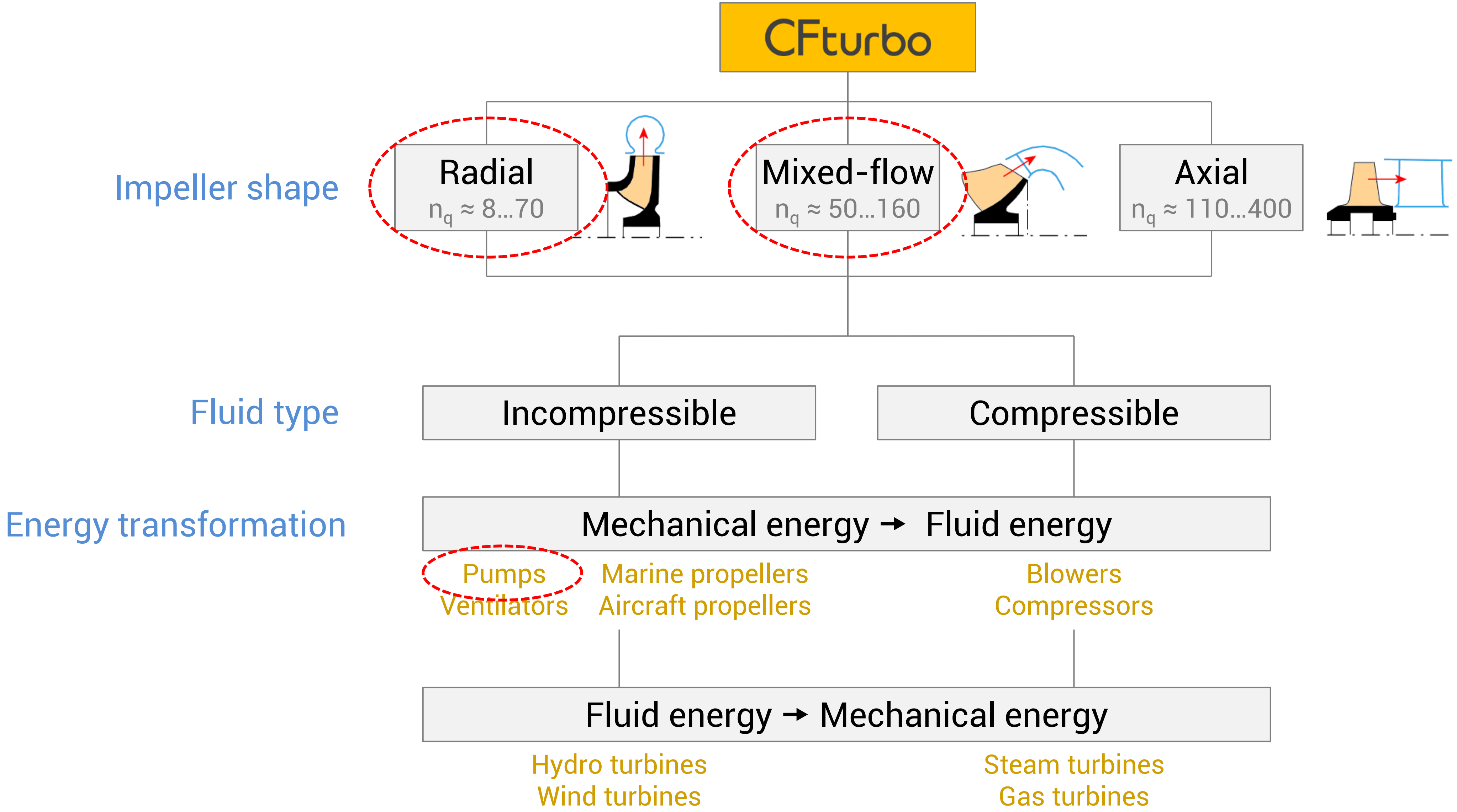
Geometric constraints
Manufacturing
Stress resistance
Geom. blade descriptions



Get 3D-CAD-model
Fluid and solid domains

Parametric geometry model
CAD/ CFD/ FEM export
define batch-mode

2 Design of centrifugal pumps with CFturbo



CFturbo

Impeller shape

Radial $n_q \approx 8\ldots70$

Mixed-flow $n_q \approx 50\ldots160$

Axial $n_q \approx 110\ldots400$

Fluid type

Incompressible

Compressible

Energy transformation

Mechanical energy → Fluid energy

Pumps
Ventilators

Marine propellers
Aircraft propellers

Blowers
Compressors

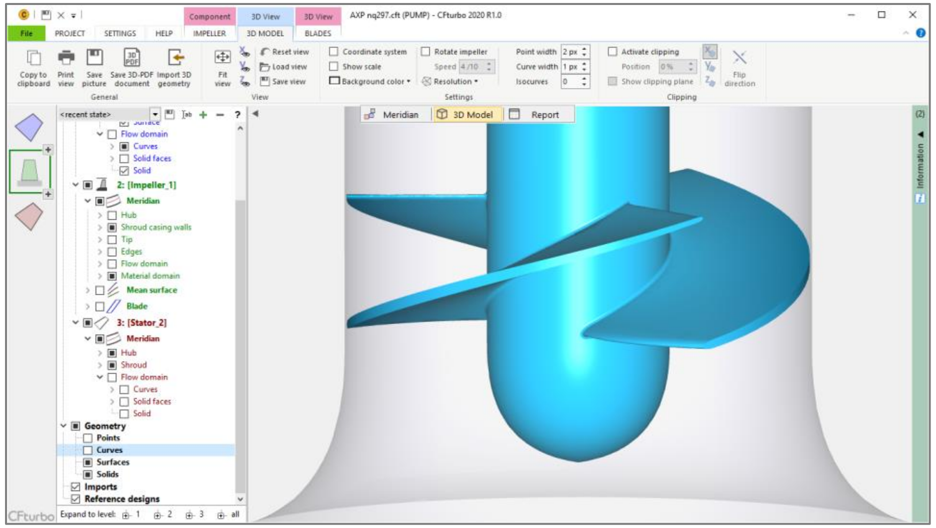
Fluid energy → Mechanical energy

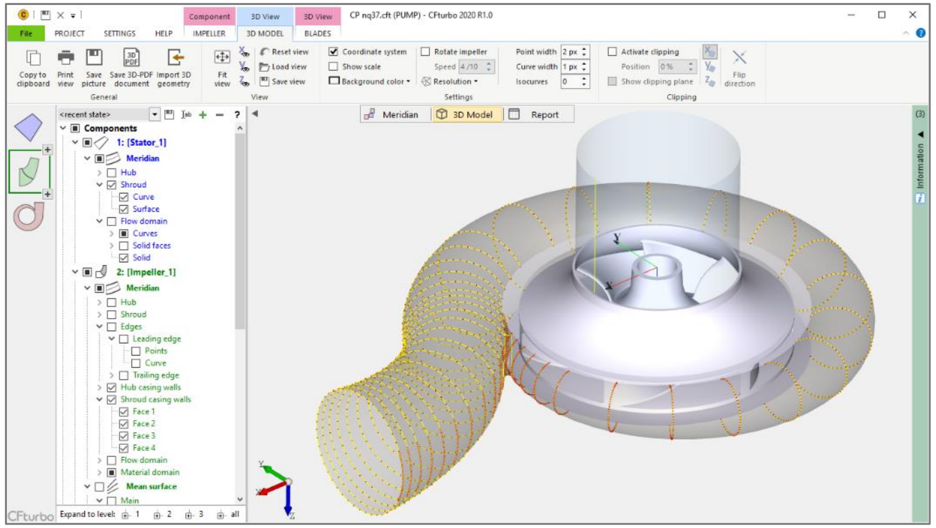
Hydro turbines
Wind turbines

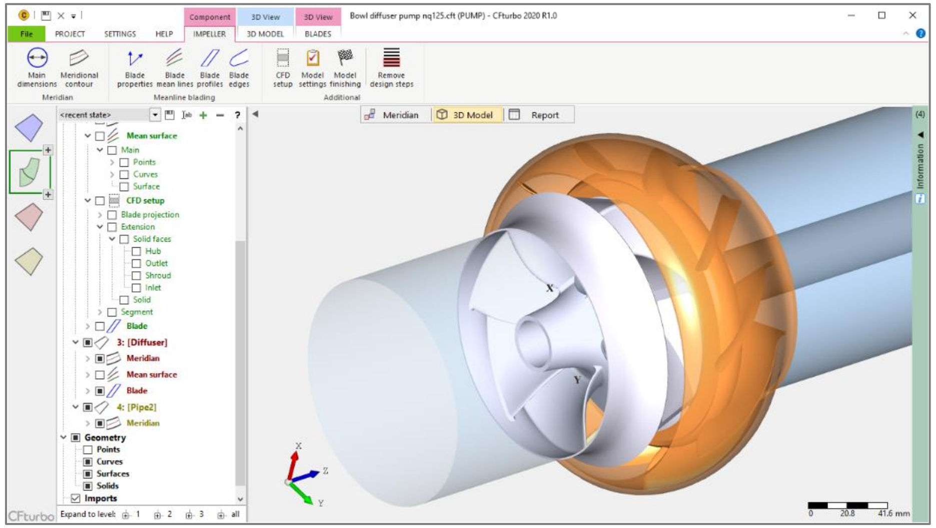
Steam turbines
Gas turbines

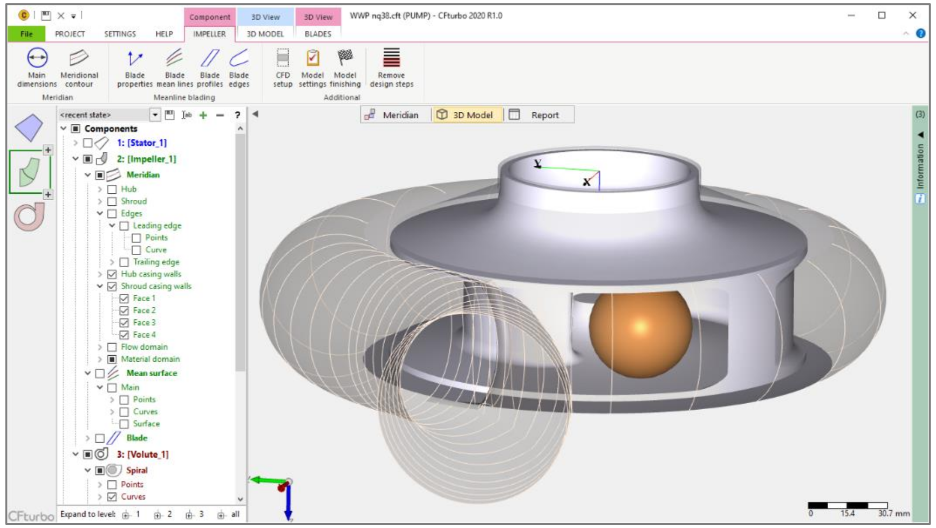
2 Design of centrifugal pumps with CFturbo

Examples – Pumps



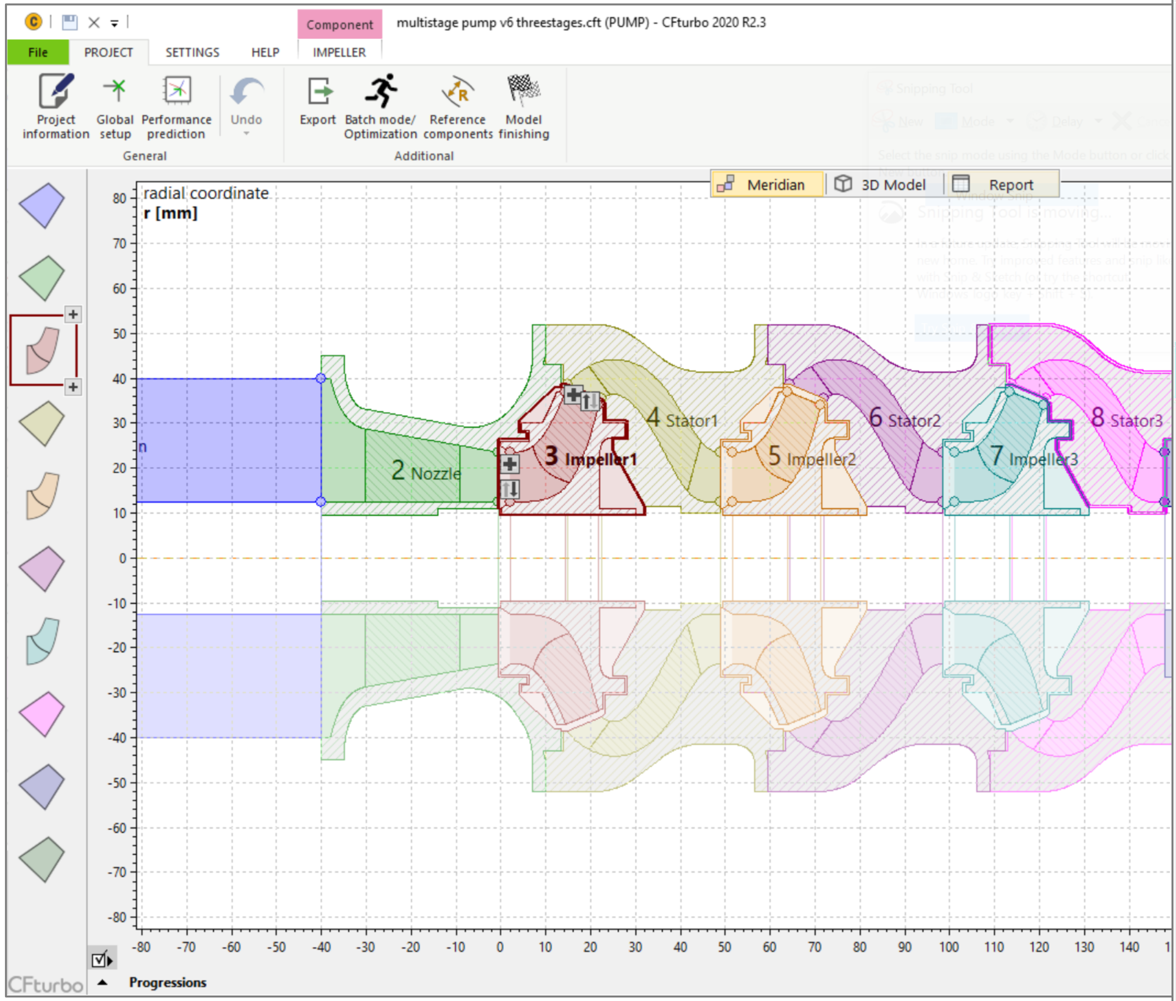


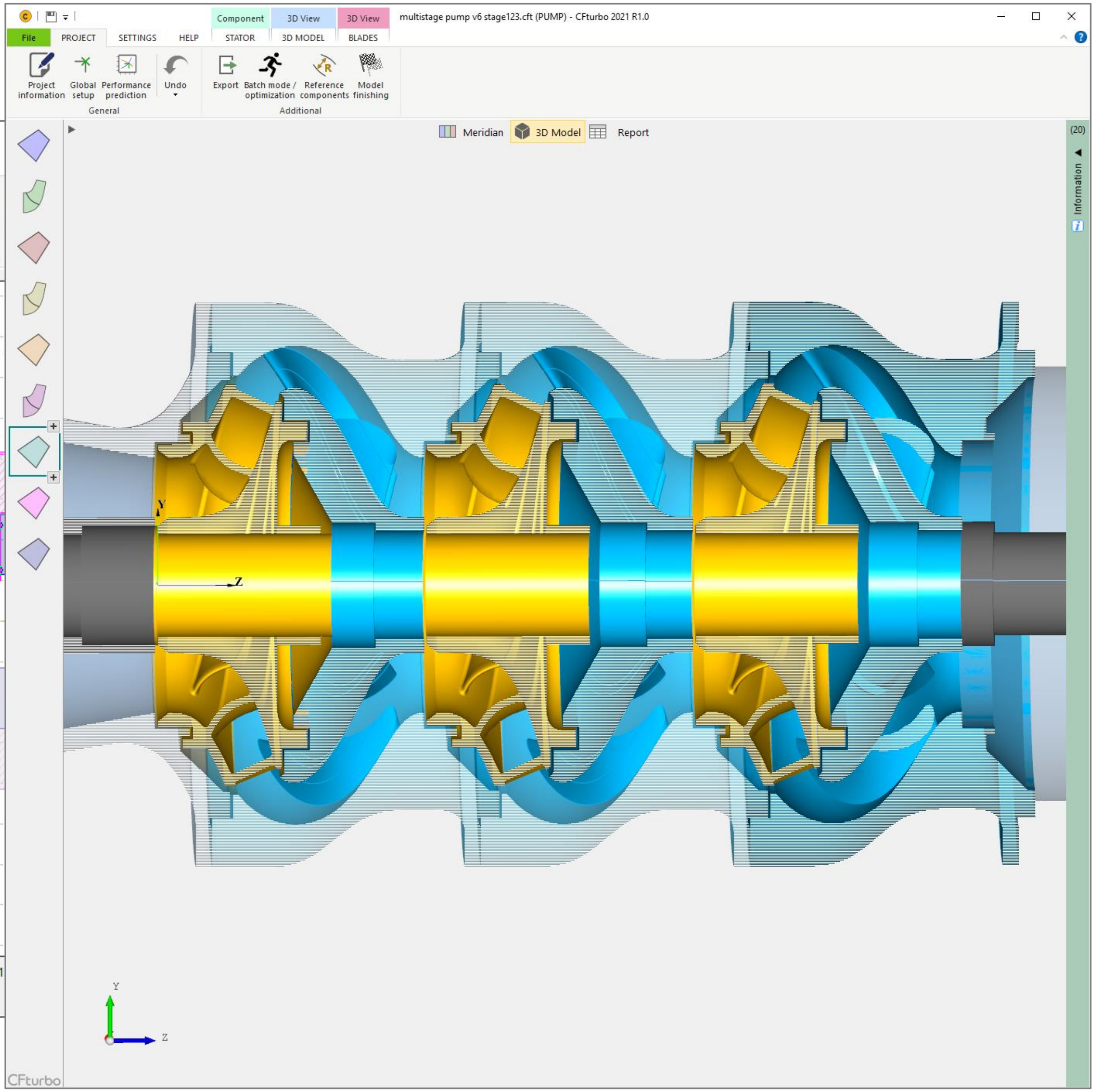




2 Design of centrifugal pumps with CFturbo

Examples – Multistage Pumps

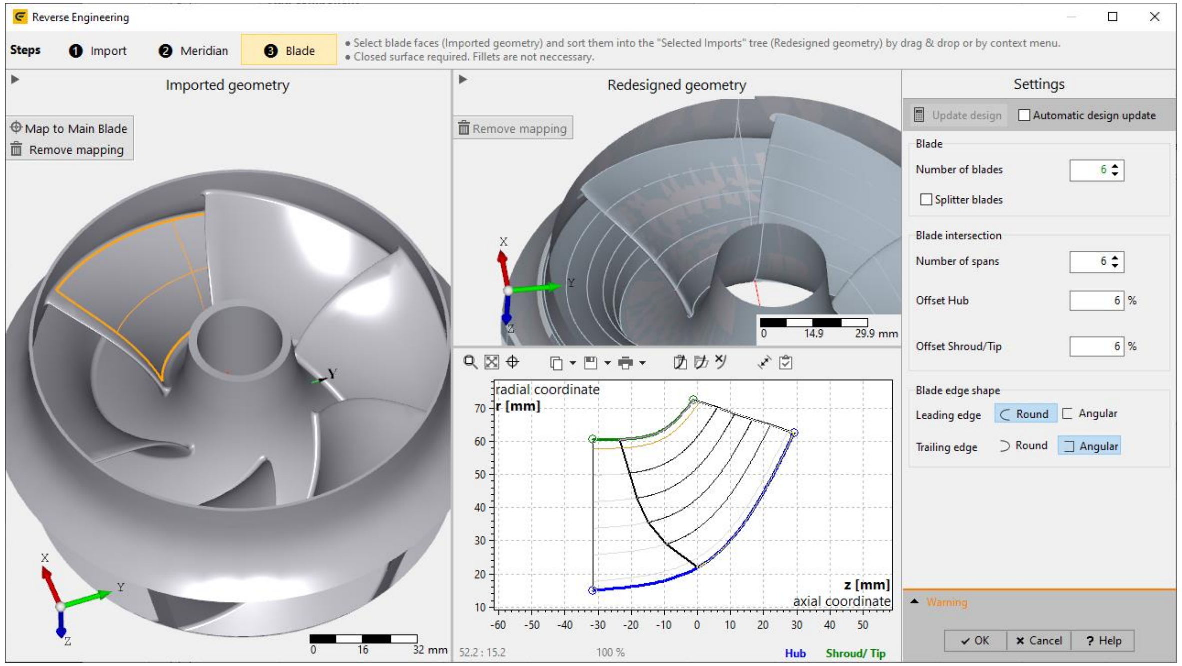




2 Design of centrifugal pumps with CFturbo

Reverse Engineering

❶ Import 3D CAD (STEP, IGES, Parasolid, BREP)



• Select blade faces (Imported geometry) and sort them into the "Selected Imports" tree (Redesigned geometry) by drag & drop or by context menu.
• Closed surface required. Fillets are not necessary.

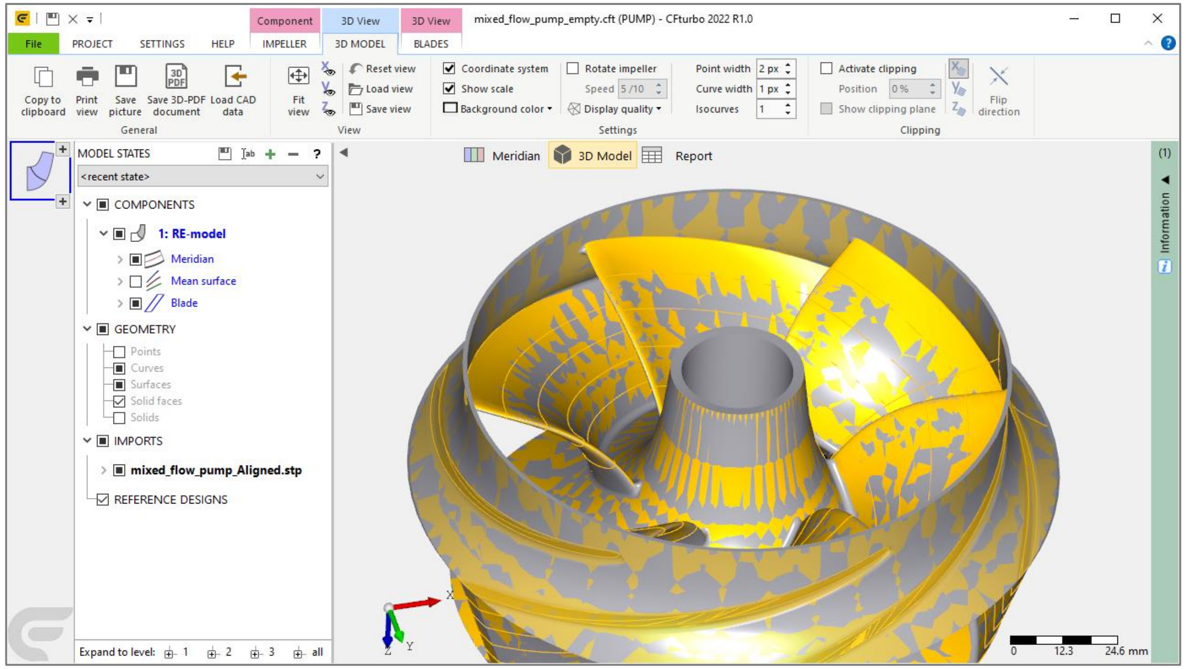
☐ Automatic design update

Blade
Number of blades: 6
☐ Splitter blades

Blade intersection
Number of spans: 6
Offset Hub: 6 %
Offset Shroud/Tip: 6 %

Blade edge shape
Leading edge: ● Round ○ Angular
Trailing edge: ○ Round ● Angular

❷ Get parametric CFturbo model

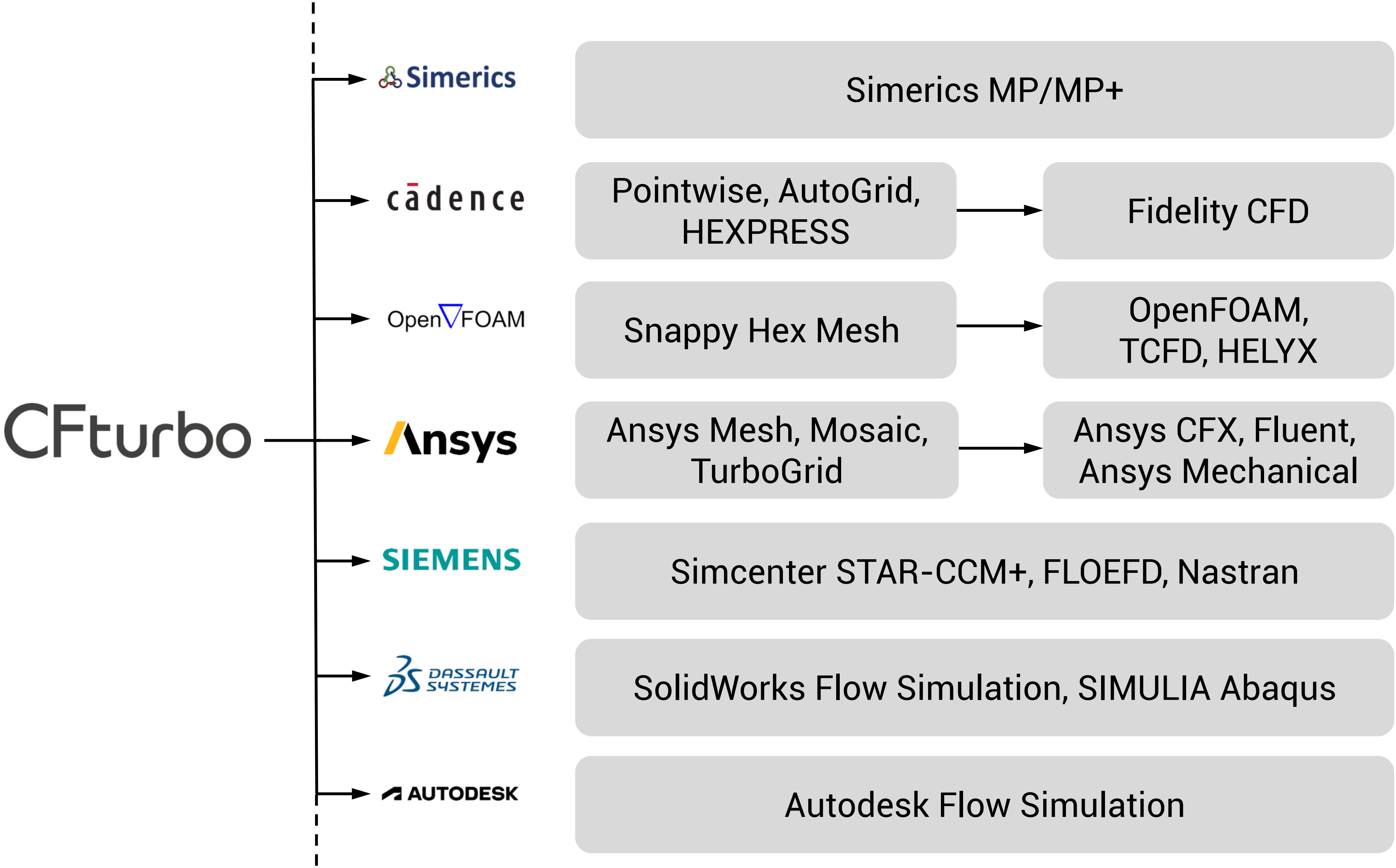


☑ Coordinate system
☑ Show scale
☐ Background color
☐ Rotate impeller
Speed: 5/10
Display quality
Point width: 2 px
Curve width: 1 px
Isocurves: 1
☐ Activate clipping
Position: 0 %
☐ Show clipping plane

Make legacy designs accessible for
- easy manual adaptions
- design exploration
- optimization

2 Design of centrifugal pumps with CFturbo

Interfaces to 3D-CFD/FEA



CFturbo

Simerics → Simerics MP/MP+

cadence → Pointwise, AutoGrid, HEXPRESS → Fidelity CFD

OpenFOAM → Snappy Hex Mesh → OpenFOAM, TCFD, HELYX

Ansys → Ansys Mesh, Mosaic, TurboGrid → Ansys CFX, Fluent, Ansys Mechanical

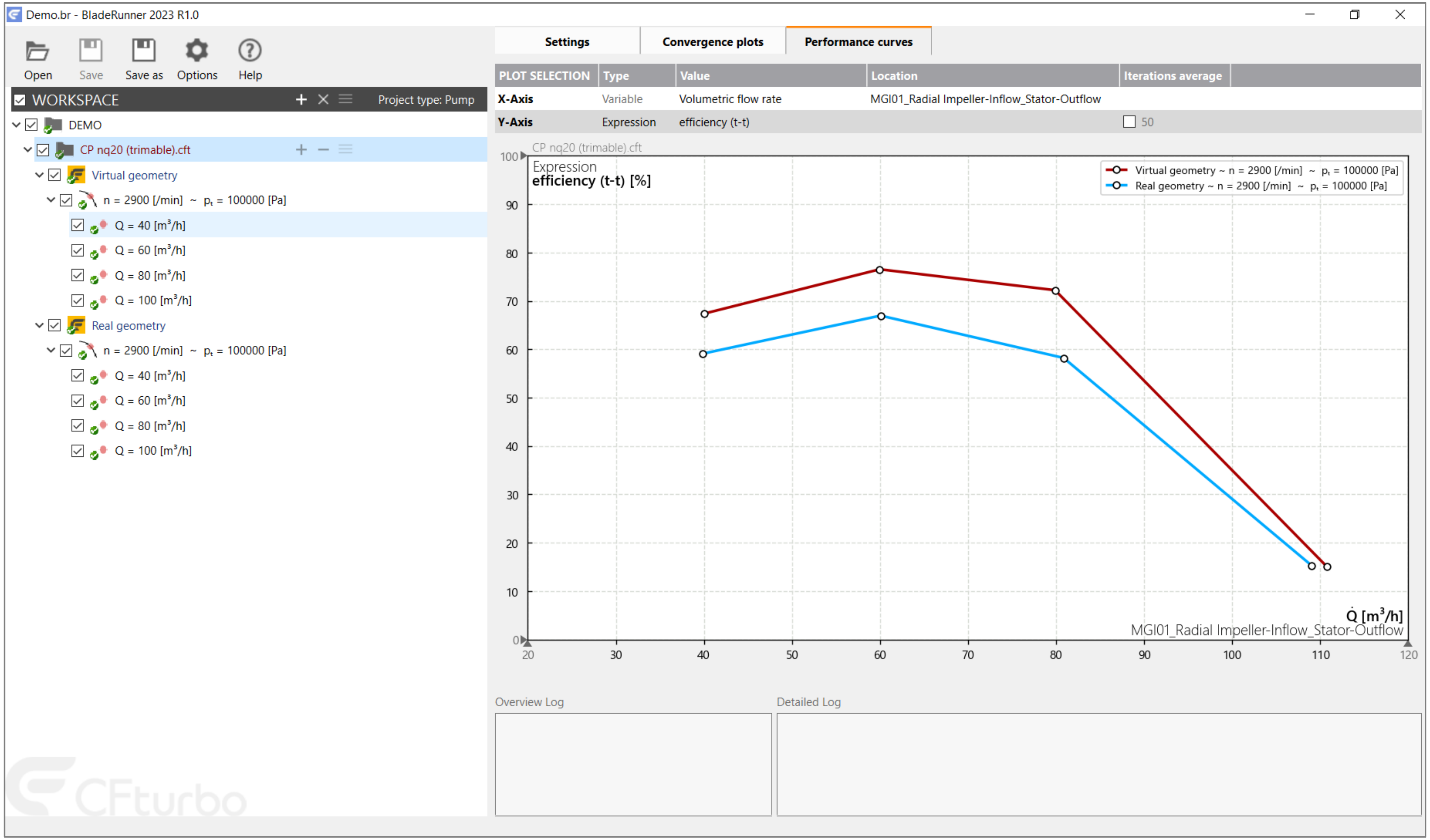
SIEMENS → Simcenter STAR-CCM+, FLOEFD, Nastran

DASSAULT SYSTEMES → SolidWorks Flow Simulation, SIMULIA Abaqus

AUTODESK → Autodesk Flow Simulation

2 Design of centrifugal pumps with CFturbo

CFturbo BladeRunner



Demo.br - BladeRunner 2023 R1.0

☑ WORKSPACE Project type: Pump

- ☑ DEMO
  - ☑ CP nq20 (trimable).cft
    - ☑ Virtual geometry
      - ☑ n = 2900 [/min] ~ p_t = 100000 [Pa]
        - ☑ Q = 40 [m³/h]
        - ☑ Q = 60 [m³/h]
        - ☑ Q = 80 [m³/h]
        - ☑ Q = 100 [m³/h]
    - ☑ Real geometry
      - ☑ n = 2900 [/min] ~ p_t = 100000 [Pa]
        - ☑ Q = 40 [m³/h]
        - ☑ Q = 60 [m³/h]
        - ☑ Q = 80 [m³/h]
        - ☑ Q = 100 [m³/h]

PLOT SELECTION	Type	Value	Location	Iterations average
X-Axis	Variable	Volumetric flow rate	MGI01_Radial Impeller-Inflow_Stator-Outflow	
Y-Axis	Expression	efficiency (t-t)		☐ 50

Topics

3 CFD and optimization made easy

Established in pump companies:

1995 - 2015
CFD

2015 - 2030
Optimization

2025 - 2040
Artificial intelligence?

Pump optimization can be done

a) by making several **manual** design modifications based on own experience + running CFD simulations

b) by using **optimization software**

advantages:

- limited pump experience necessary
- less manpower required

disadvantages:

- additional software required
- more computing power required

Optimization
DAKOTA, DesignXplorer, HEEDS, Isight, Minamo, modeFRONTIER, optiSLang, …

Design
CFturbo

Simulation
CCM+, CFX, Fidelity CFD, OpenFOAM, Simerics, …

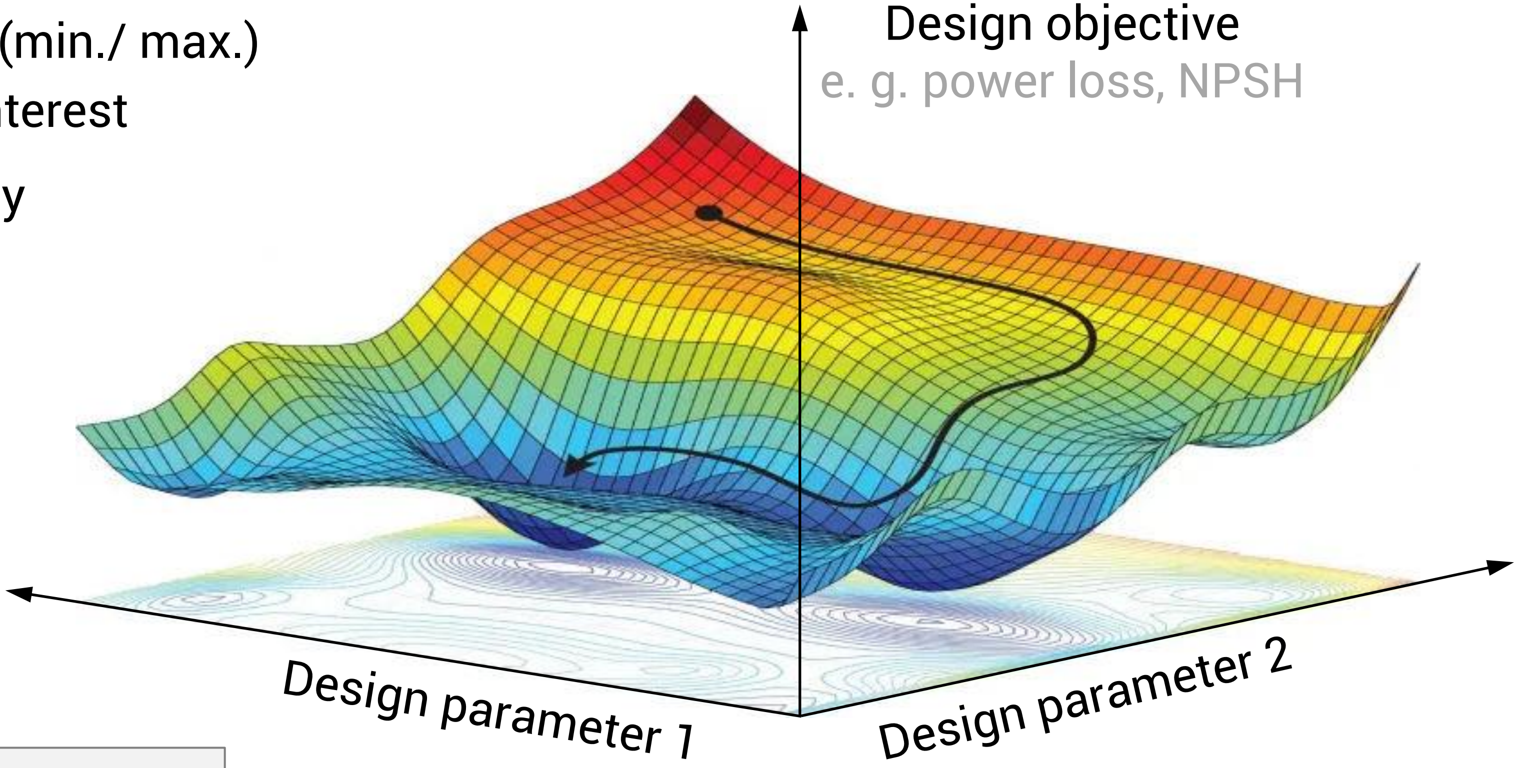
Optimization results depend on quality of CFD-solution:

- steady-state CFD is ok
- use more simplified/ loss model-based/ frictionless flow simulation makes no sense

3 CFD and optimization made easy

Important terms:

- **Objective**: determine extreme values (min./ max.) of a single or multiple quantities of interest
- **Constraints**: limit quantities optionally
- **Parameters**: input design quantities



e. g. number of blades,
suction diameter, blade angles,
meridional contour, blade shape, …

Typical procedure:

1) **Sensitivity analysis (DoE)**:
rough dependency of objective on parameters

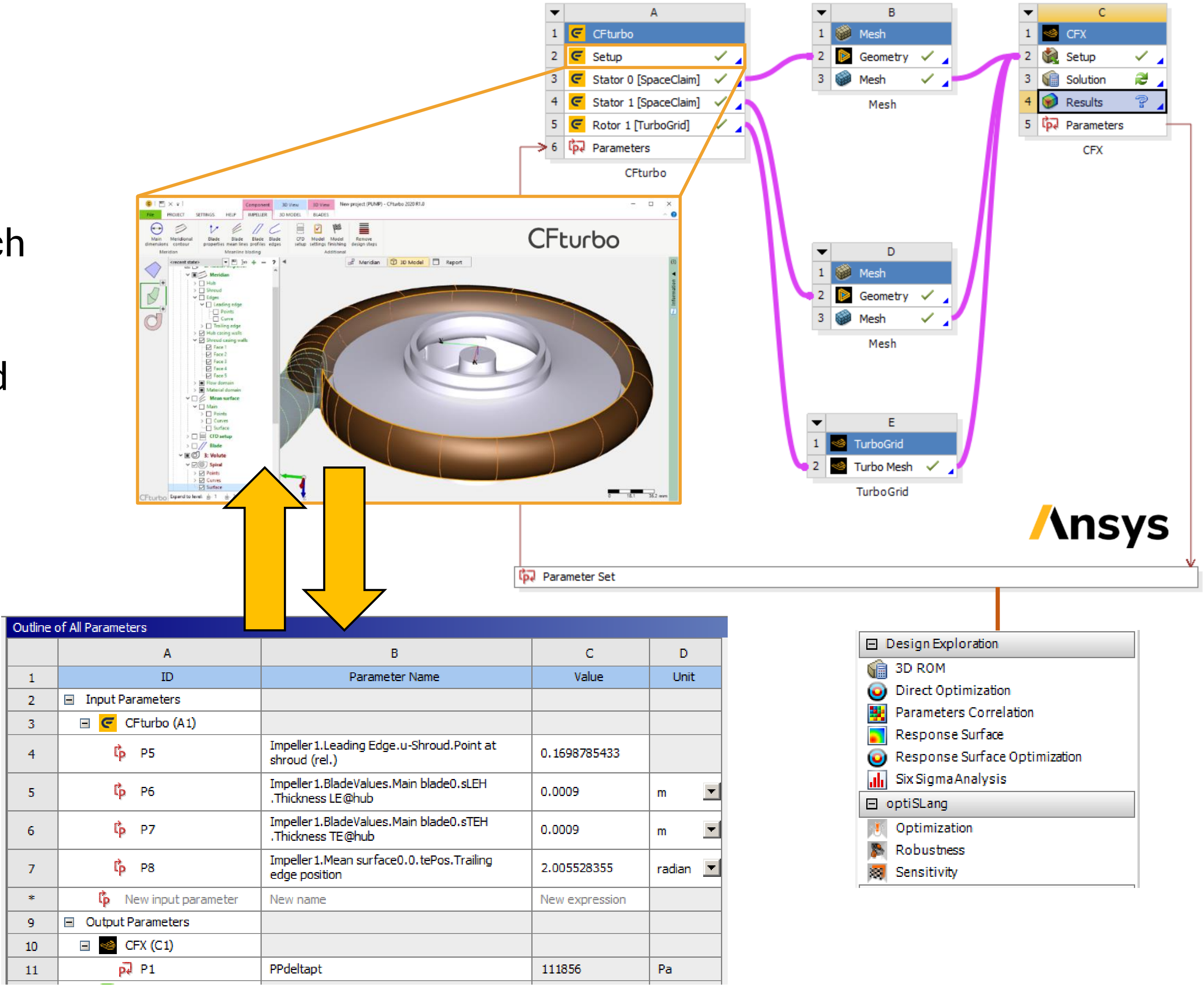
2) **Optimization**: find best design

3 CFD and optimization made easy

CFturbo in Ansys Workbench

CFturbo workbench extension…

- integrates CFturbo into Ansys Workbench
- allows bi-directional parameter updates
- creates named selections for bodies and faces automatically
- improves data processing in Ansys Meshing, CFX-Pre, Fluent, CFD Post, Ansys Mechanical
- enables automatic turbomachinery optimization using DesignXplorer or optiSLang



Outline of All Parameters

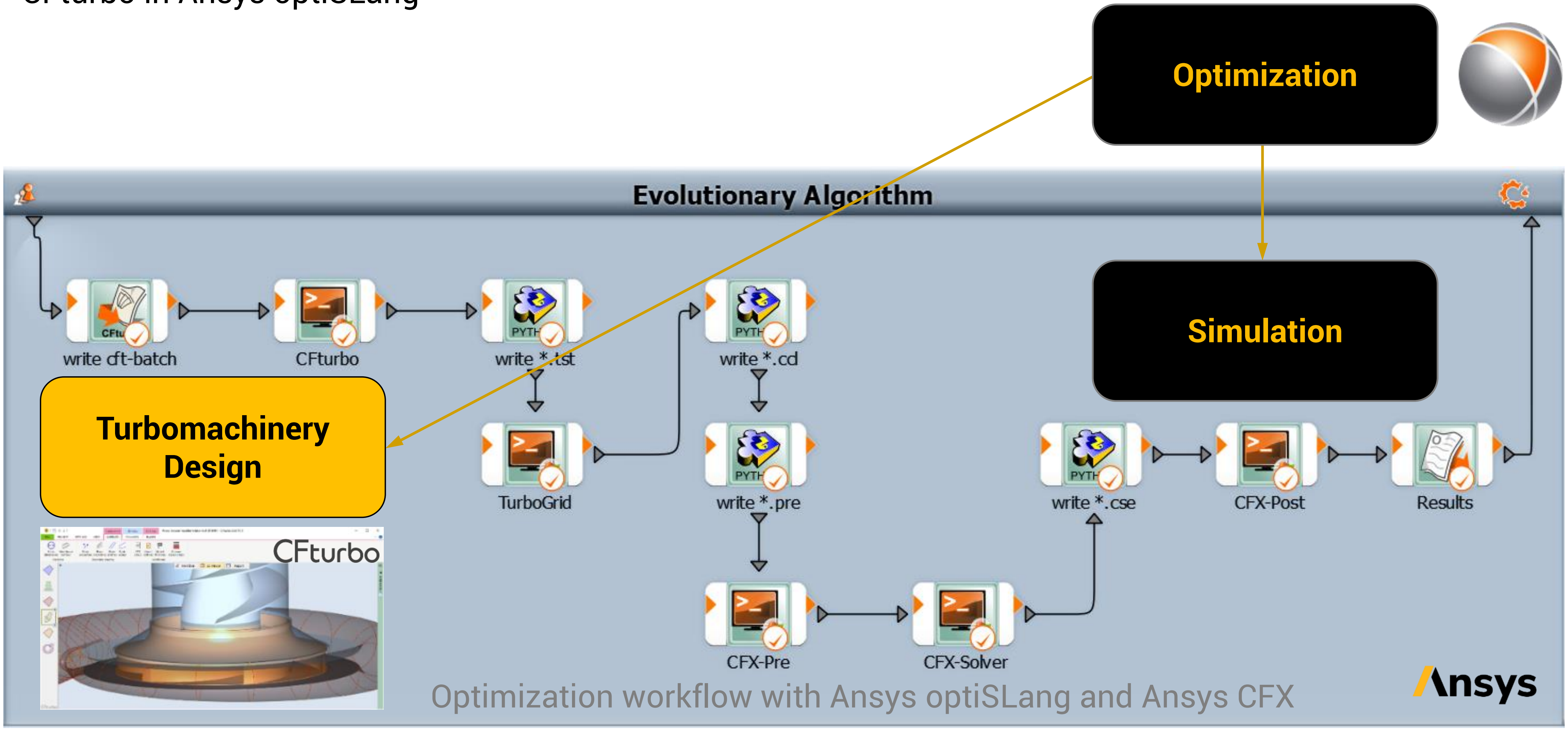
	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
3	CFturbo (A1)			
4	P5	Impeller1.Leading Edge.u-Shroud.Point at shroud (rel.)	0.1698785433	
5	P6	Impeller1.BladeValues.Main blade0.sLEH .Thickness LE@hub	0.0009	m
6	P7	Impeller1.BladeValues.Main blade0.sTEH .Thickness TE@hub	0.0009	m
7	P8	Impeller1.Mean surface0.0.tePos.Trailing edge position	2.005528355	radian
*	New input parameter	New name	New expression	
9	Output Parameters			
10	CFX (C1)			
11	P1	PPdeltapt	111856	Pa

Design Exploration
- 3D ROM
- Direct Optimization
- Parameters Correlation
- Response Surface
- Response Surface Optimization
- Six Sigma Analysis

optiSLang
- Optimization
- Robustness
- Sensitivity

3 CFD and optimization made easy

CFturbo in Ansys optiSLang



Optimization

Simulation

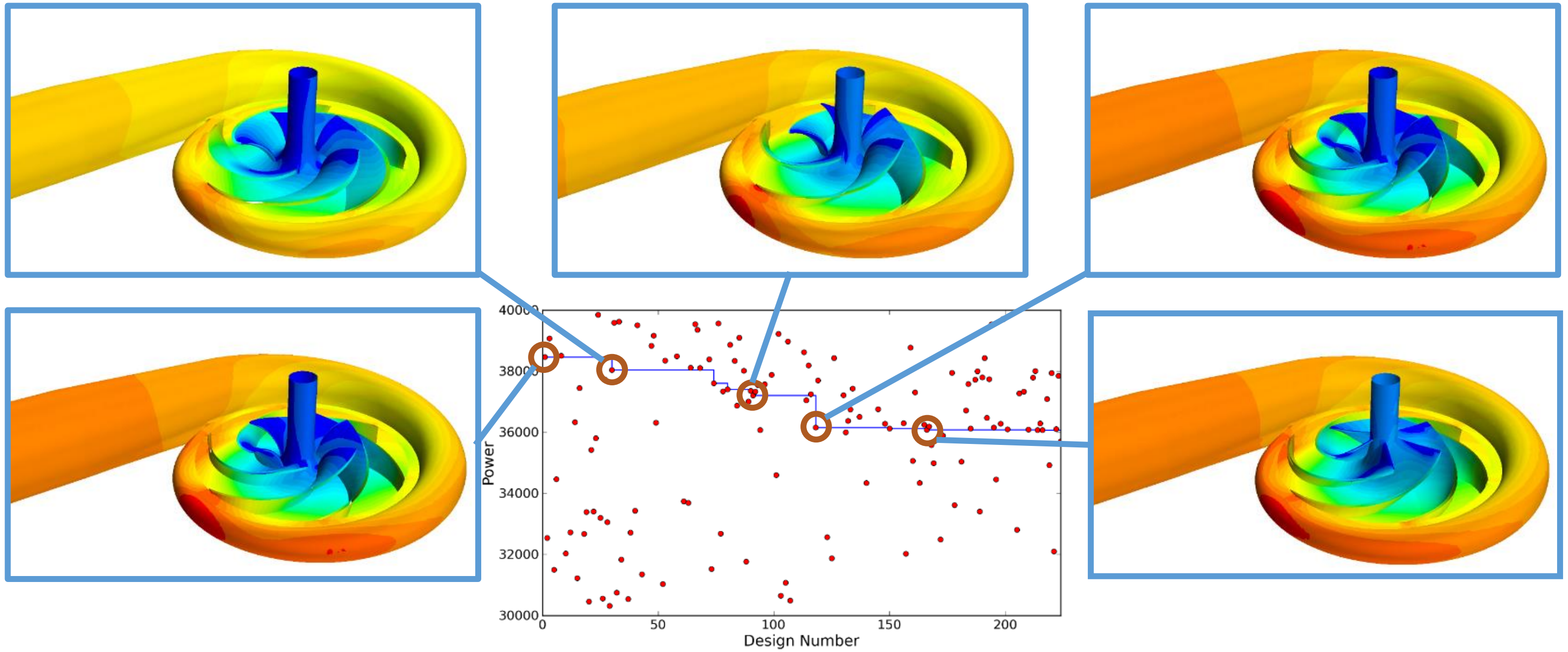
Turbomachinery Design

Optimization workflow with Ansys optiSLang and Ansys CFX

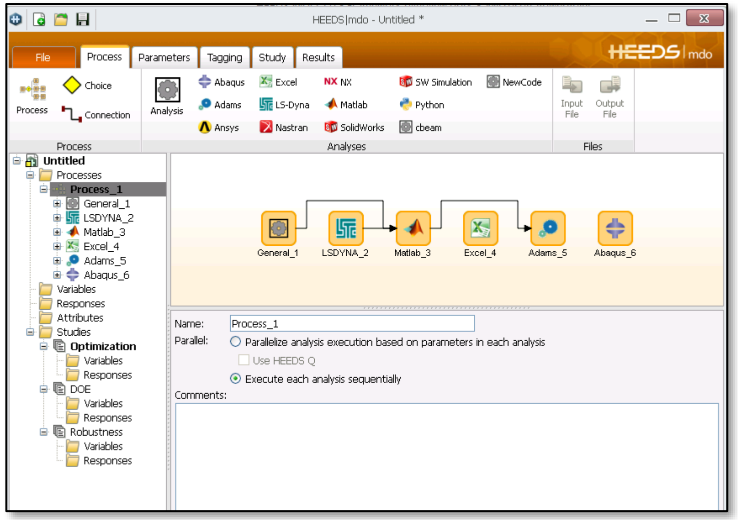
Any other CFD solver can be integrated

3 CFD and optimization made easy

CFturbo in Simcenter HEEDS/ STAR-CCM+



Process Automation



Name: Process_1

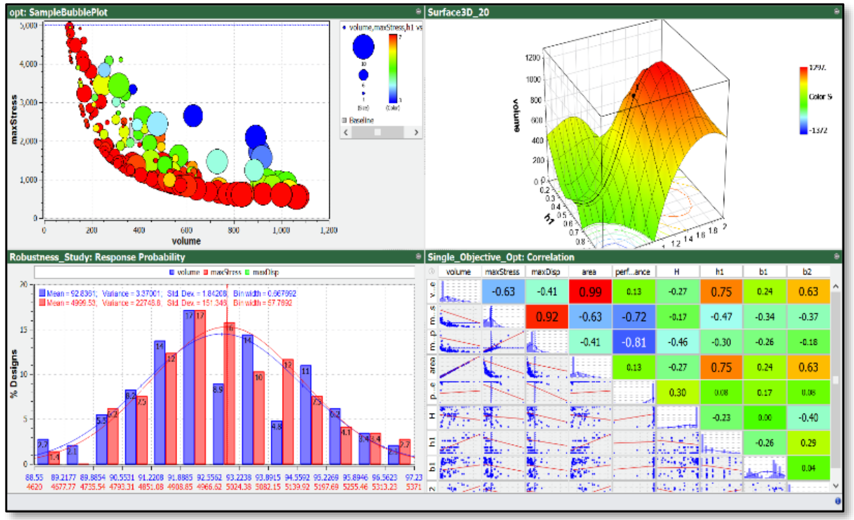
Parallel: ○ Parallelize analysis execution based on parameters in each analysis

☐ Use HEEDS Q

● Execute each analysis sequentially

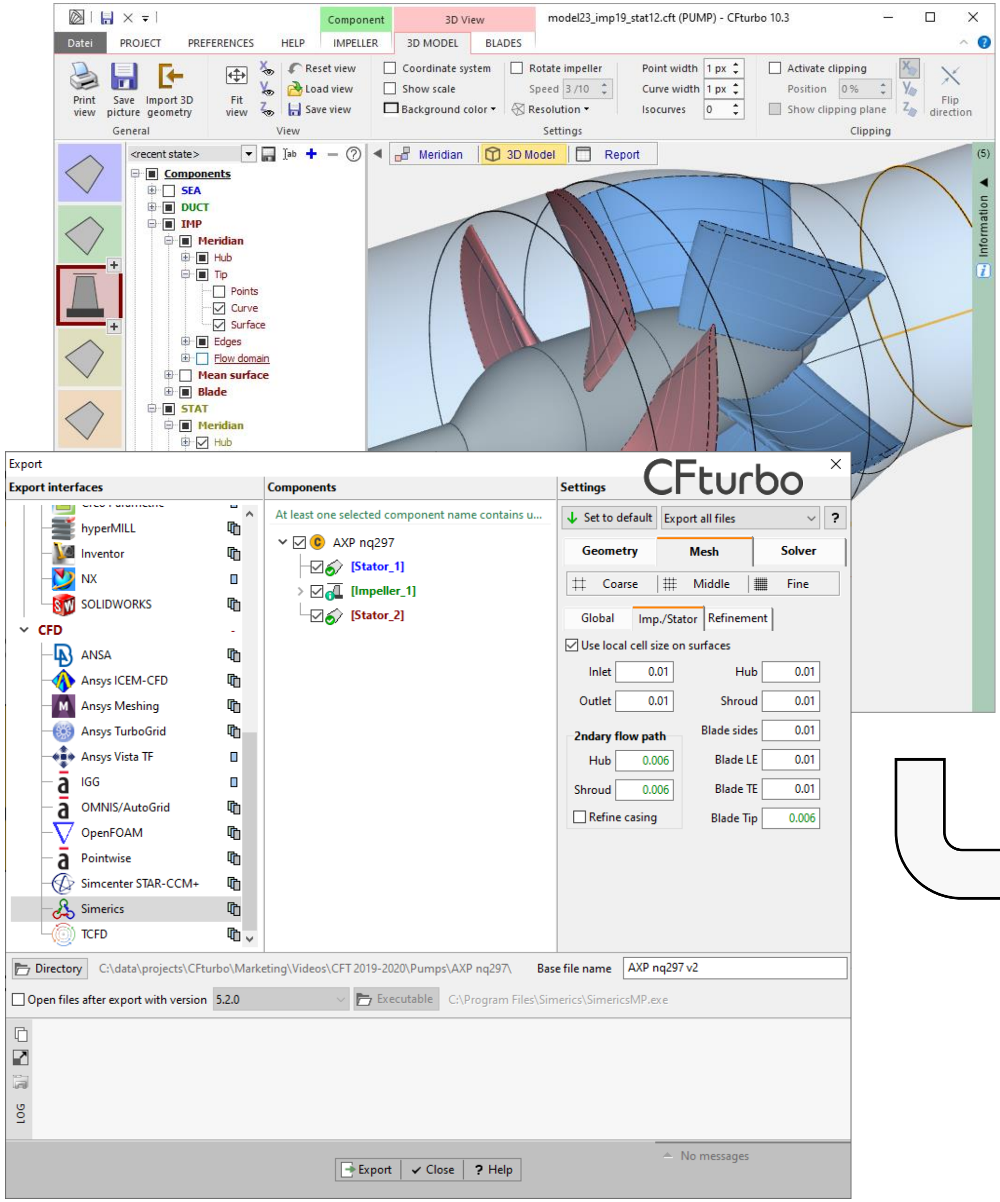
Comments:

Design Exploration



3 CFD and optimization made easy

CFturbo + Simerics MP



Settings

Set to default | Export all files | ?

Geometry | Mesh | Solver

Coarse | Middle | Fine

Global | Imp./Stator | Refinement

☑ Use local cell size on surfaces

Inlet	0.01	Hub	0.01
Outlet	0.01	Shroud	0.01
		Blade sides	0.01

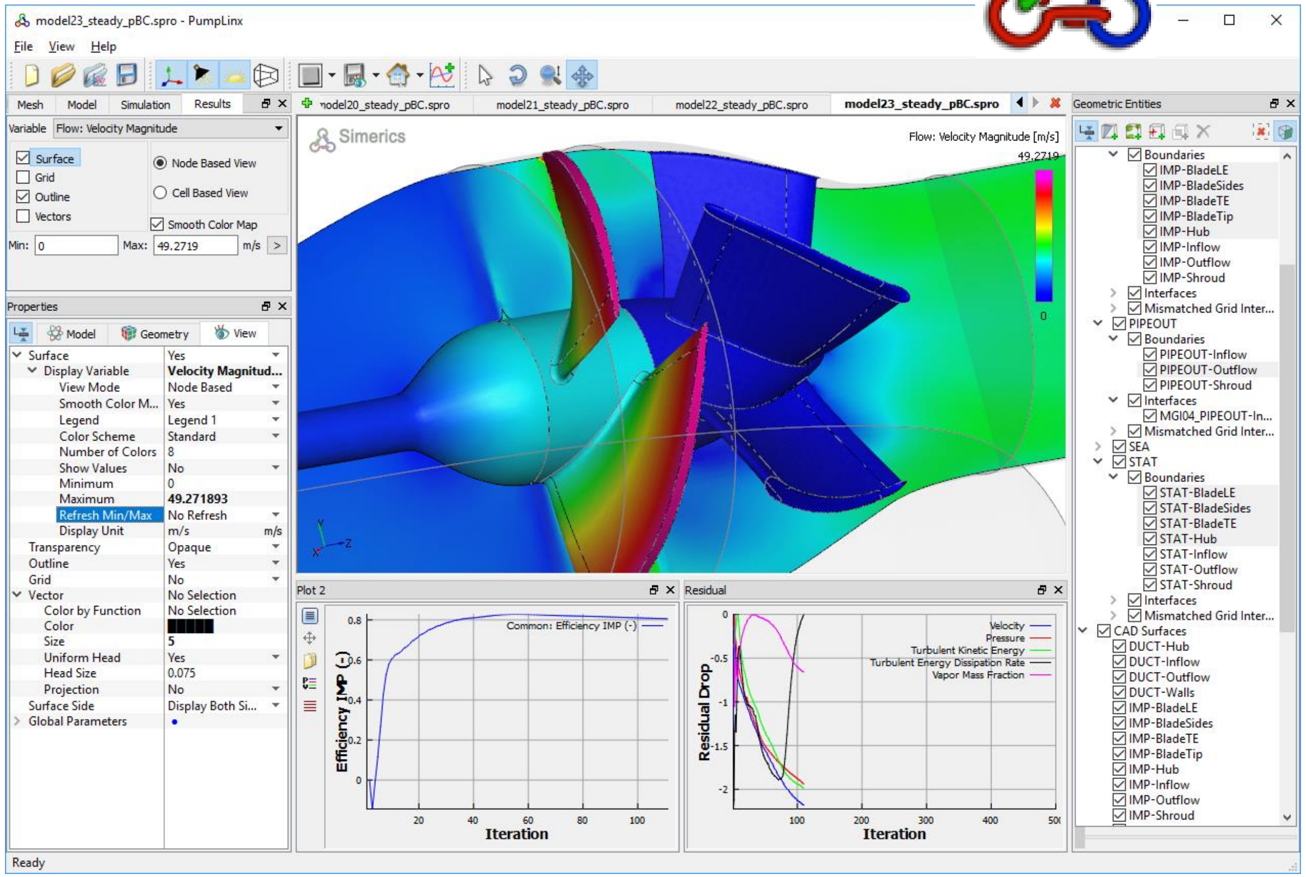
2ndary flow path

Hub	0.006	Blade LE	0.01
Shroud	0.006	Blade TE	0.01
☐ Refine casing		Blade Tip	0.006

Directory C:\data\projects\CFturbo\Marketing\Videos\CFT 2019-2020\Pumps\AXP nq297\ Base file name AXP nq297 v2

☐ Open files after export with version 5.2.0 Executable C:\Program Files\Simerics\SimericsMP.exe

- ✓ Define mesh parameters and solver settings in CFturbo
- ✓ Immediate start of simulation for the CFturbo design point
- ✓ Python scripts for batch runs to get performance curves



Variable Flow: Velocity Magnitude

☑ Surface ● Node Based View
☐ Grid
☑ Outline ○ Cell Based View
☐ Vectors ☑ Smooth Color Map

Min: 0 Max: 49.2719 m/s

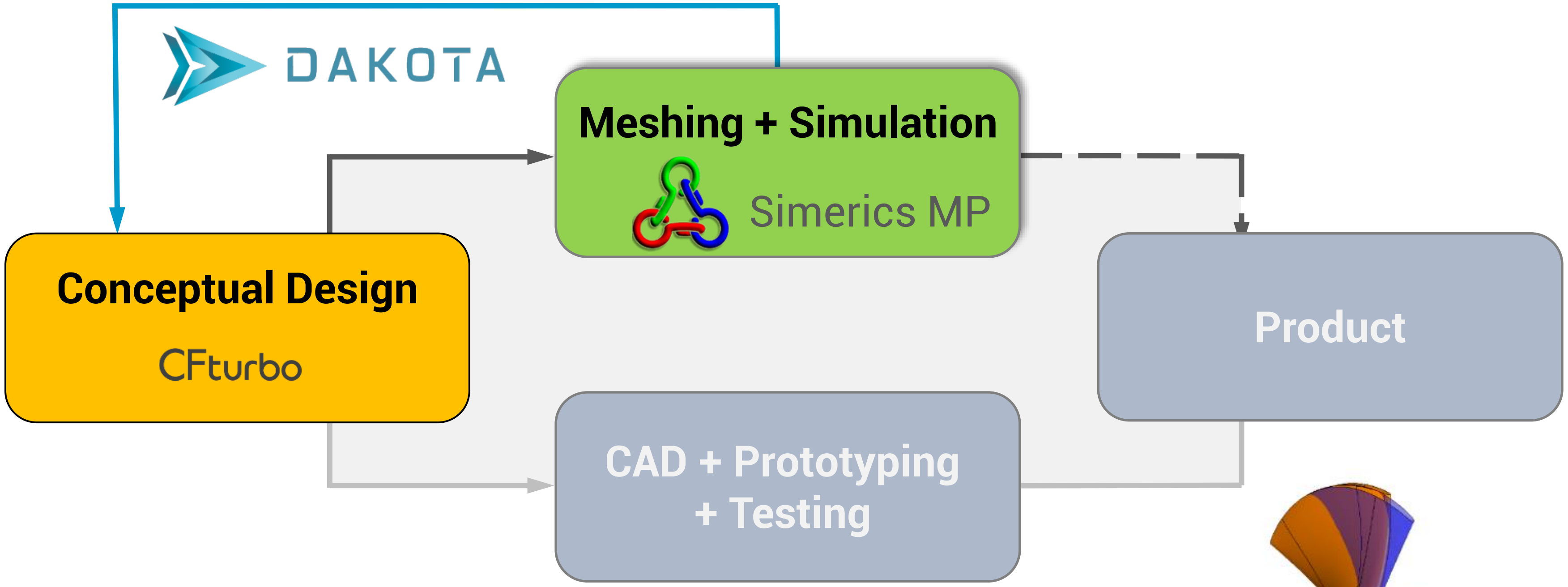
Properties

Model | Geometry | View

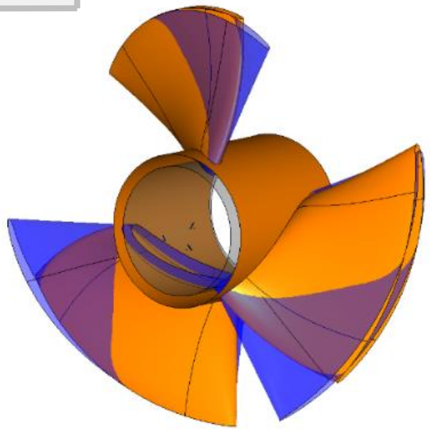
Surface	Yes
Display Variable	Velocity Magnitud...
View Mode	Node Based
Smooth Color M...	Yes
Legend	Legend 1
Color Scheme	Standard
Number of Colors	8
Show Values	No
Minimum	0
Maximum	49.271893
Refresh Min/Max	No Refresh
Display Unit	m/s
Transparency	Opaque
Outline	Yes
Grid	No
Vector	No Selection
Color by Function	No Selection
Color	■
Size	5
Uniform Head	Yes
Head Size	0.075
Projection	No
Surface Side	Display Both Si...
Global Parameters	

3 CFD and optimization made easy

CFturbo in DAKOTA



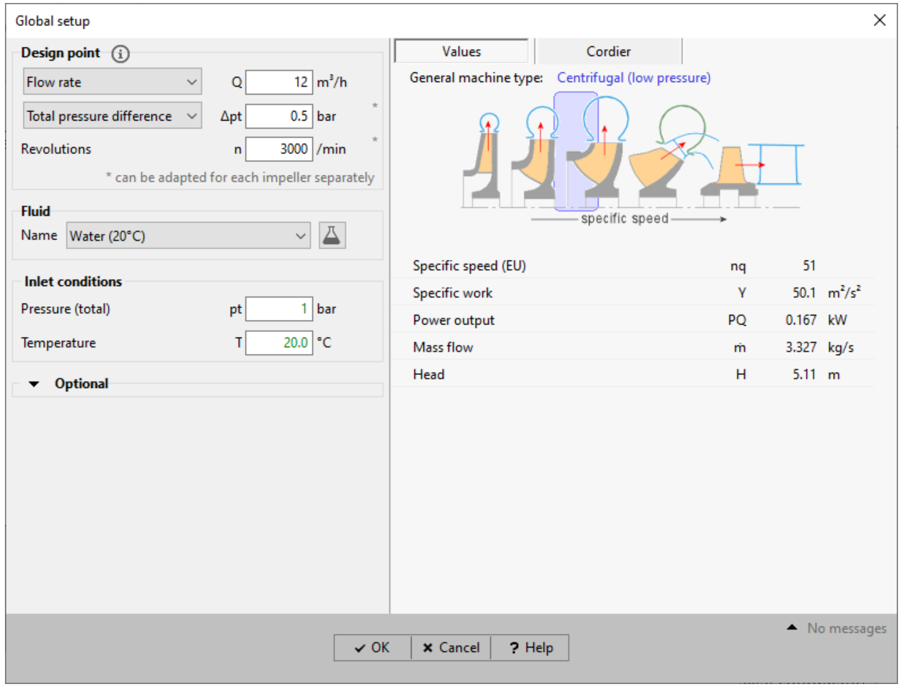
Optimization workflow with DAKOTA and Simerics MP



Topics

4 Project examples ❶ Centrifugal pump optimization

Application: small water pump



Global setup

Design point

Flow rate: Q 12 m³/h

Total pressure difference: Δpt 0.5 bar *

Revolutions: n 3000 /min *

* can be adapted for each impeller separately

Fluid

Name: Water (20°C)

Inlet conditions

Pressure (total): pt 1 bar

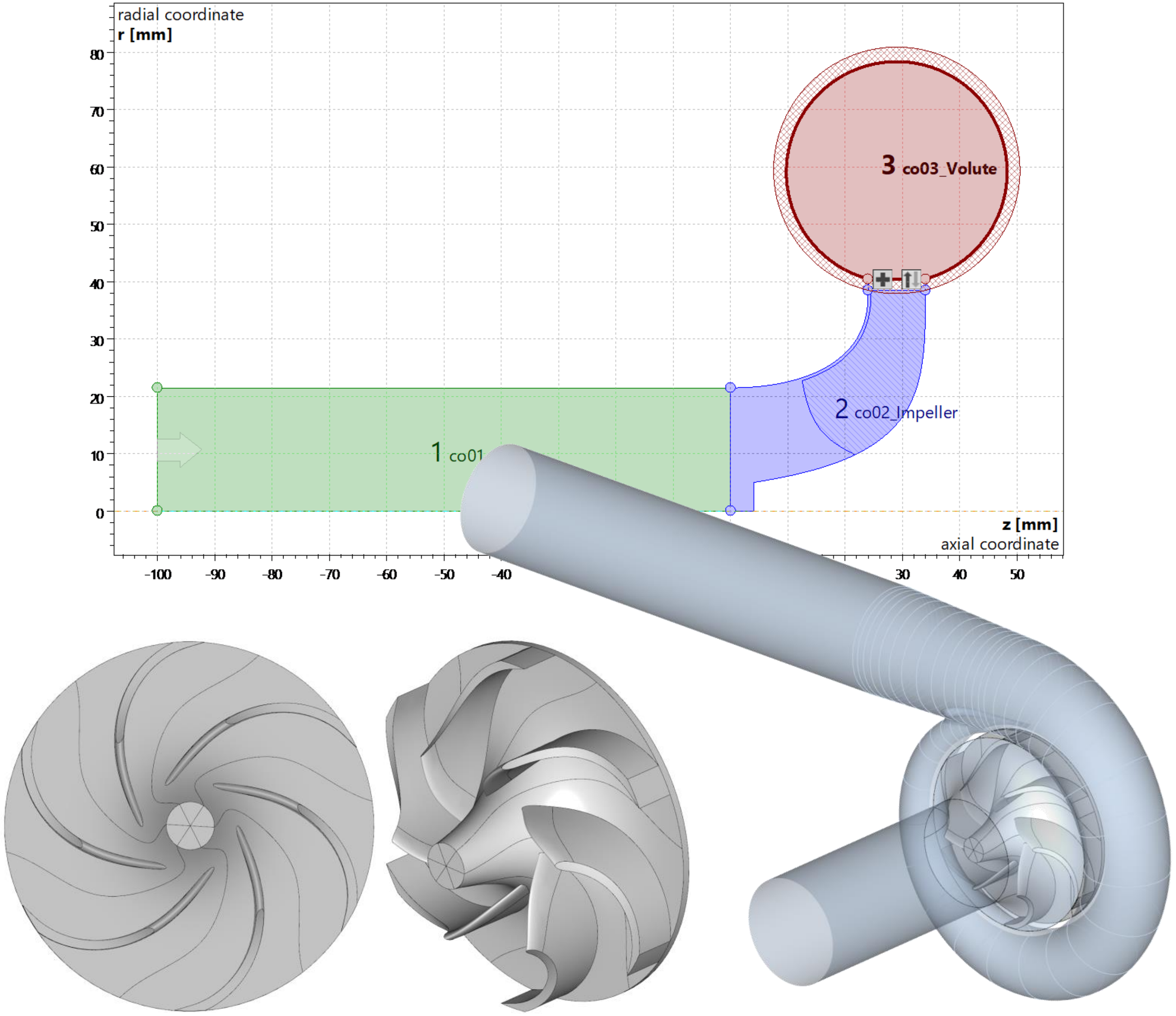
Temperature: T 20.0 °C

▼ Optional

Values | Cordier

General machine type: Centrifugal (low pressure)

Specific speed (EU)	nq	51	
Specific work	Y	50.1	m²/s²
Power output	PQ	0.167	kW
Mass flow	ṁ	3.327	kg/s
Head	H	5.11	m



Auto-completion of all design steps with default values to get an automatic design within seconds

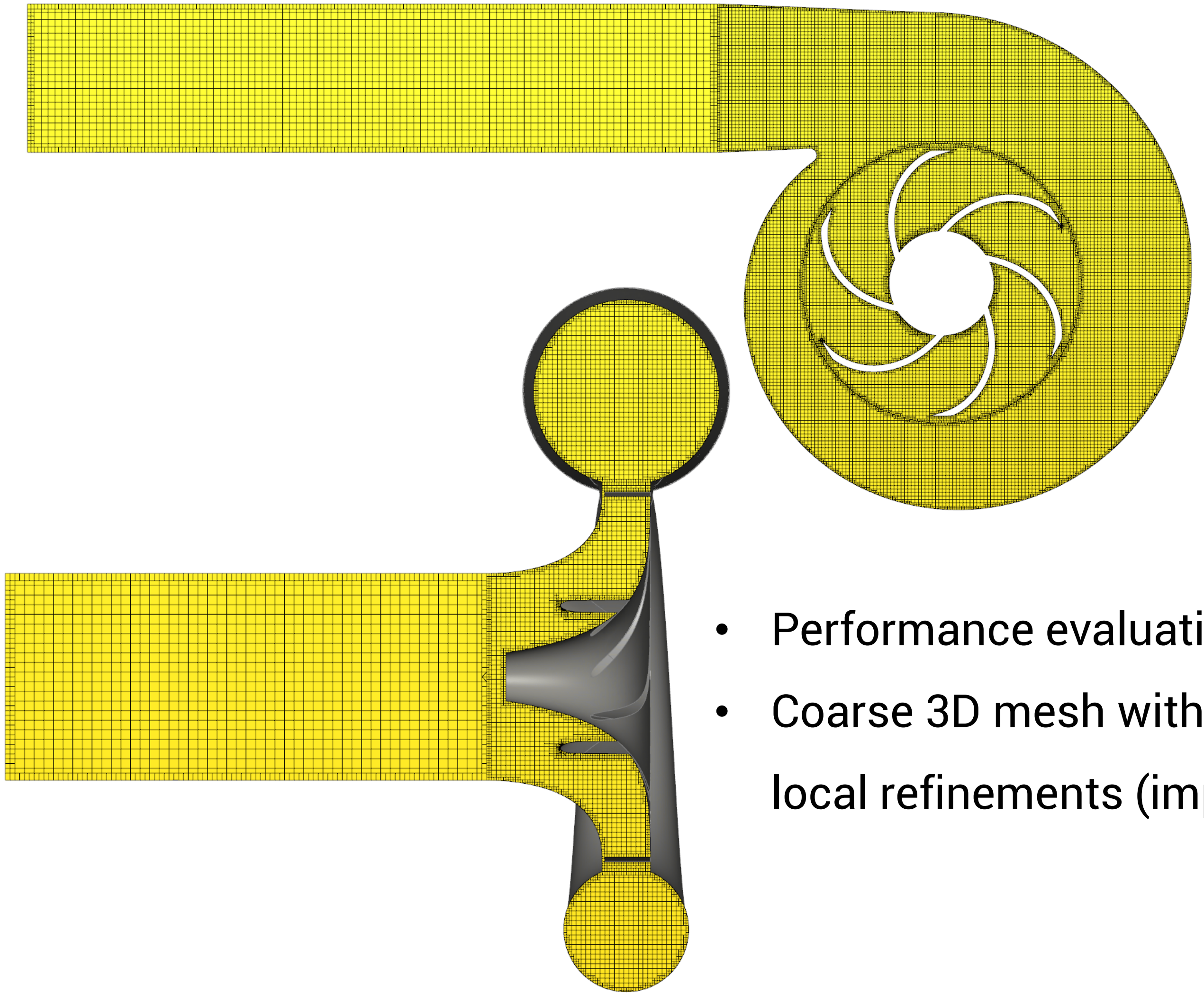
Limitation

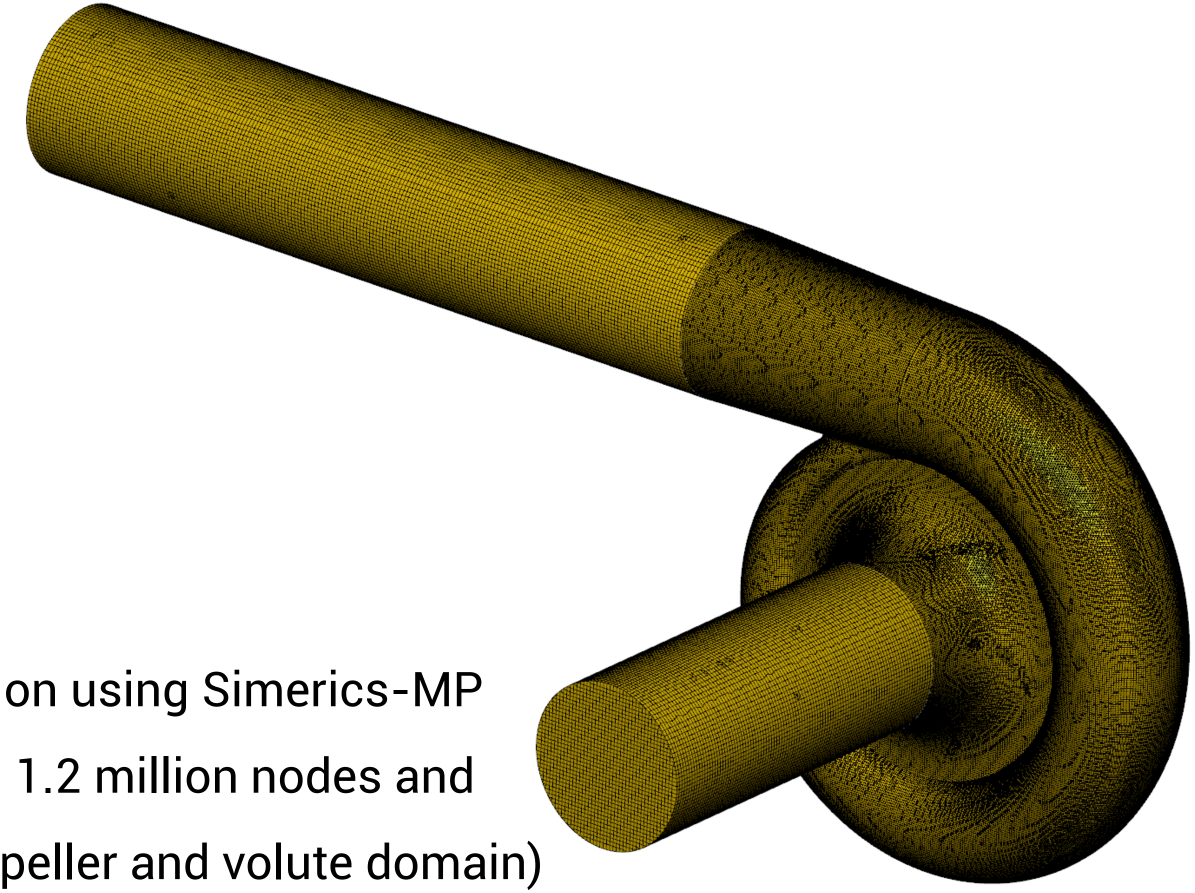
Free-form 2D (axial) blade shape

4 Project examples

❶ Centrifugal pump optimization

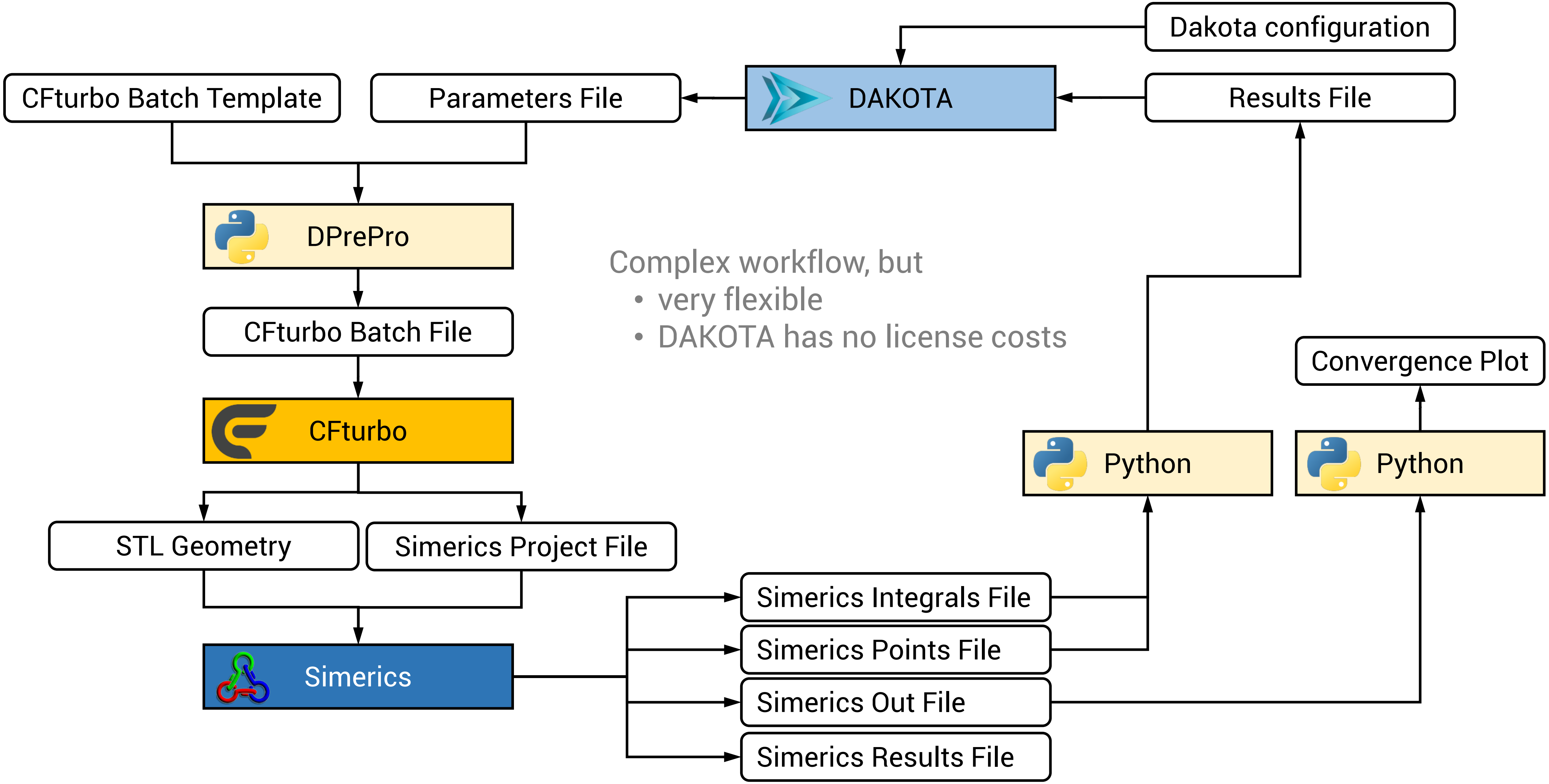
Objective
Maximize efficiency while keeping head constant





- Performance evaluation using Simerics-MP
- Coarse 3D mesh with 1.2 million nodes and local refinements (impeller and volute domain)

4 Project examples — ❶ Centrifugal pump optimization



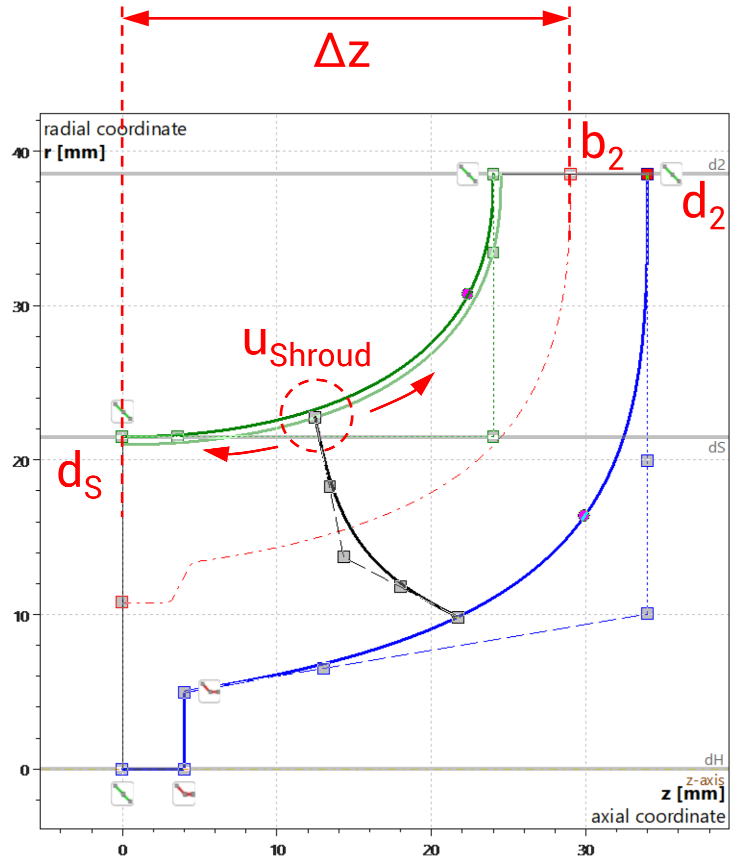
Complex workflow, but
- very flexible
- DAKOTA has no license costs

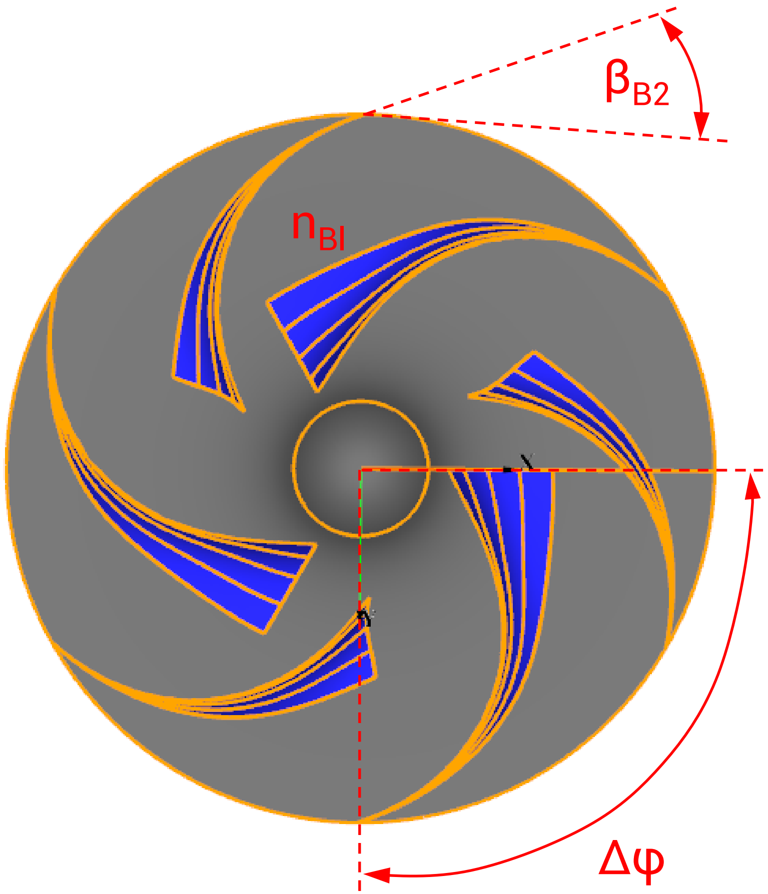
4 Project examples ❶ Centrifugal pump optimization

10 geometry parameters were used for sampling and optimization studies

8 impeller parameters

- Suction diameter d_S
- Outer diameter d_2
- Outlet width b_2
- Axial extension Δz
- Leading edge rel. position u_{Shroud}
- Blade trailing edge angle β_{B2}
- Number of blades n_{Bl}
- Blade wrap angle $\Delta\varphi$

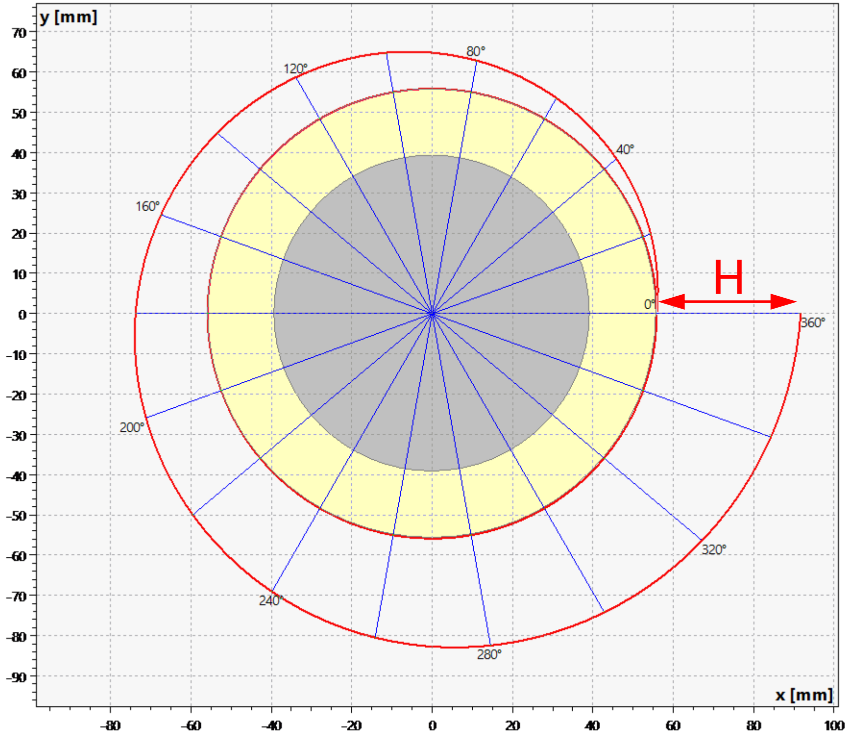


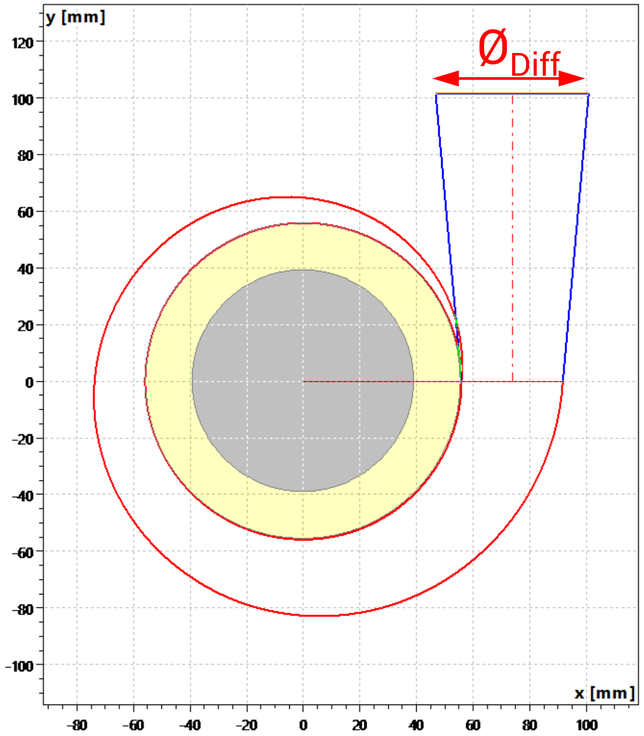


10 geometry parameters were used for sampling and optimization studies

2 volute parameters

- Volute swirl exponent (specifies area progression in respect to volute wrap and end cross section H)
- Volute diffuser end cross section diameter $Ø_{Diff}$





Define lower/ upper bounds for the geometry parameters before exploring the parameter space

Geometry Parameter	Symbol	Unit	Lower limit ▼	Initial value	▲ Upper limit
Impeller suction diameter	d_S	mm	39	43	47
Impeller outlet width	b_2	mm	9	10	11
Impeller outer diameter	d_2	mm	75	77	79
Impeller axial extension	Δz	mm	10	29	30
Impeller leading edge rel. position	u_{Shroud}	%	10	37	40
Impeller number of blades	n_{Bl}	-	5	6	7
Impeller blade trailing edge angle	$\beta_{B2,H}$	deg	15	15	30
Impeller blade wrap angle	$\Delta\varphi$	deg	80	90	110
Volute swirl exponent (Pfleiderer theory)	x	mm	0	1	2
Volute diffuser end cross section diameter	$Ø_{Diff}$	mm	39	43	47

4 Project examples

❶ Centrifugal pump optimization

Generate 200 near-random samples using Latin-Hypercube-Sampling (LHS)

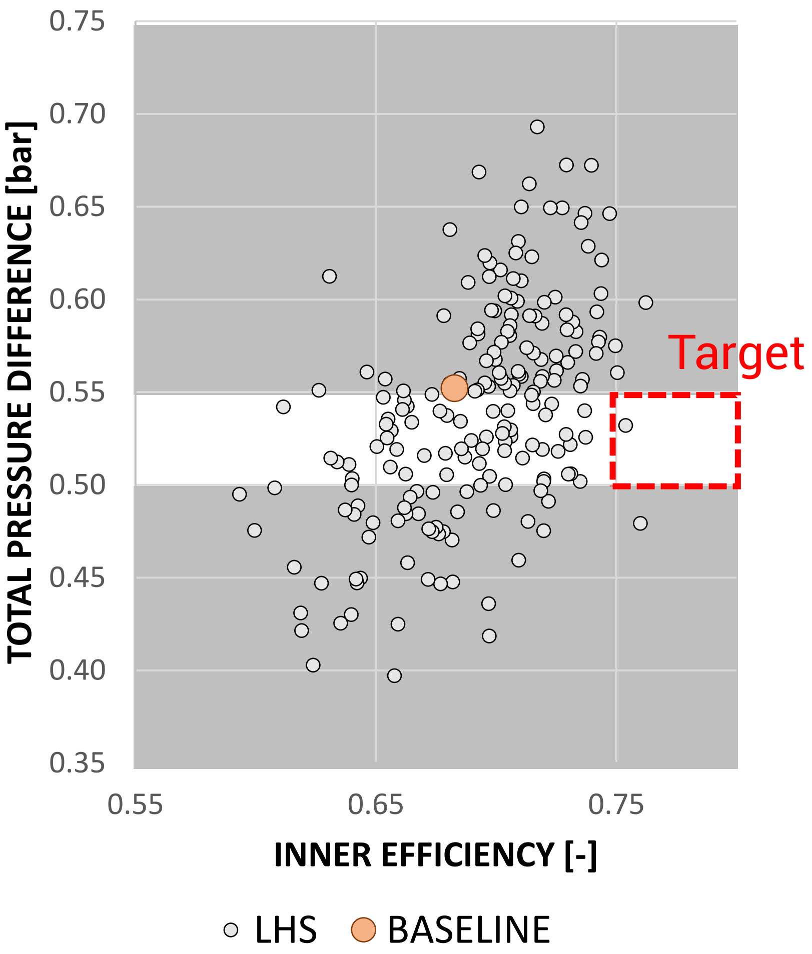
- 12 hours on Intel Xeon W-2255 workstation, steady-state CFD

⇨ Correlation matrix among all inputs and outputs

	d_S	b_2	d_2	Δz	u_{Shroud}	$\beta_{B2,H}$	$\Delta\varphi$	x	$Ø_{Diff}$	n_{Bl}	η	Δp_t
d_S	1.00											
b_2	-0.02	1.00										
d_2	0.02	0.02	1.00									
Δz	0.03	0.00	-0.01	1.00								
u_{Shroud}	0.02	0.02	0.00	0.01	1.00							
$\beta_{B2,H}$	0.03	0.00	-0.03	0.00	-0.03	1.00						
$\Delta\varphi$	0.01	-0.02	-0.04	0.00	0.01	-0.02	1.00					
x	0.02	-0.02	-0.02	-0.03	0.00	-0.02	-0.02	1.00				
$Ø_{Diff}$	0.00	0.02	0.01	0.03	0.01	-0.01	0.01	-0.02	1.00			
n_{Bl}	-0.06	-0.01	0.03	-0.03	0.01	-0.01	0.03	-0.07	0.05	1.00		
η	-0.56	0.01	0.08	-0.05	-0.22	-0.25	0.06	0.30	0.01	0.38	1.00	
Δp_t	-0.13	0.32	0.50	0.38	-0.17	0.01	-0.20	0.15	0.04	0.47	0.53	1.00

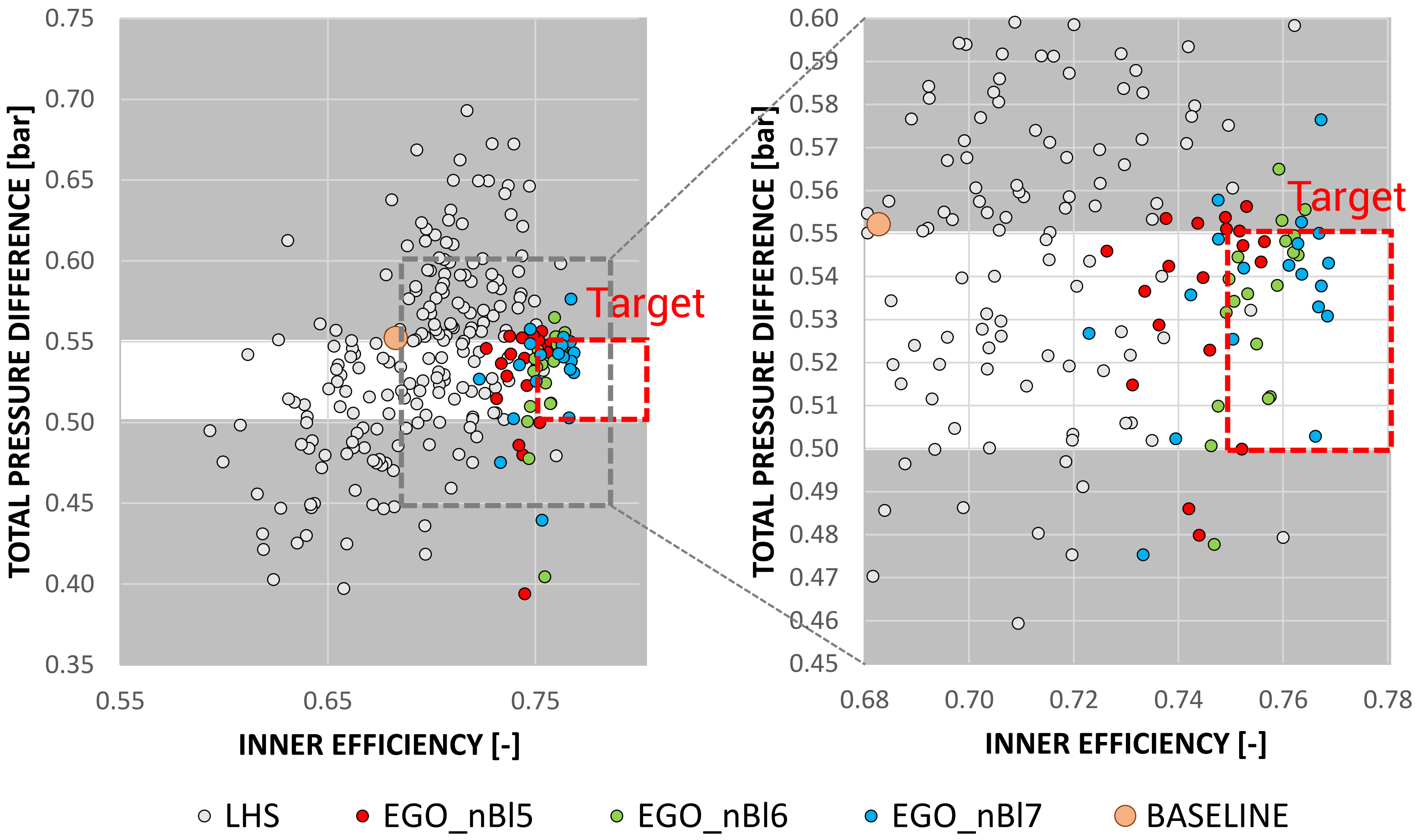
4 Project examples ❶ Centrifugal pump optimization

200 **sample designs** (LHS)



60 **optimized designs** via the efficient global optimization (EGO)

- ▶ 4 hours on AMD Threadripper Pro 3945WX, steady-state CFD



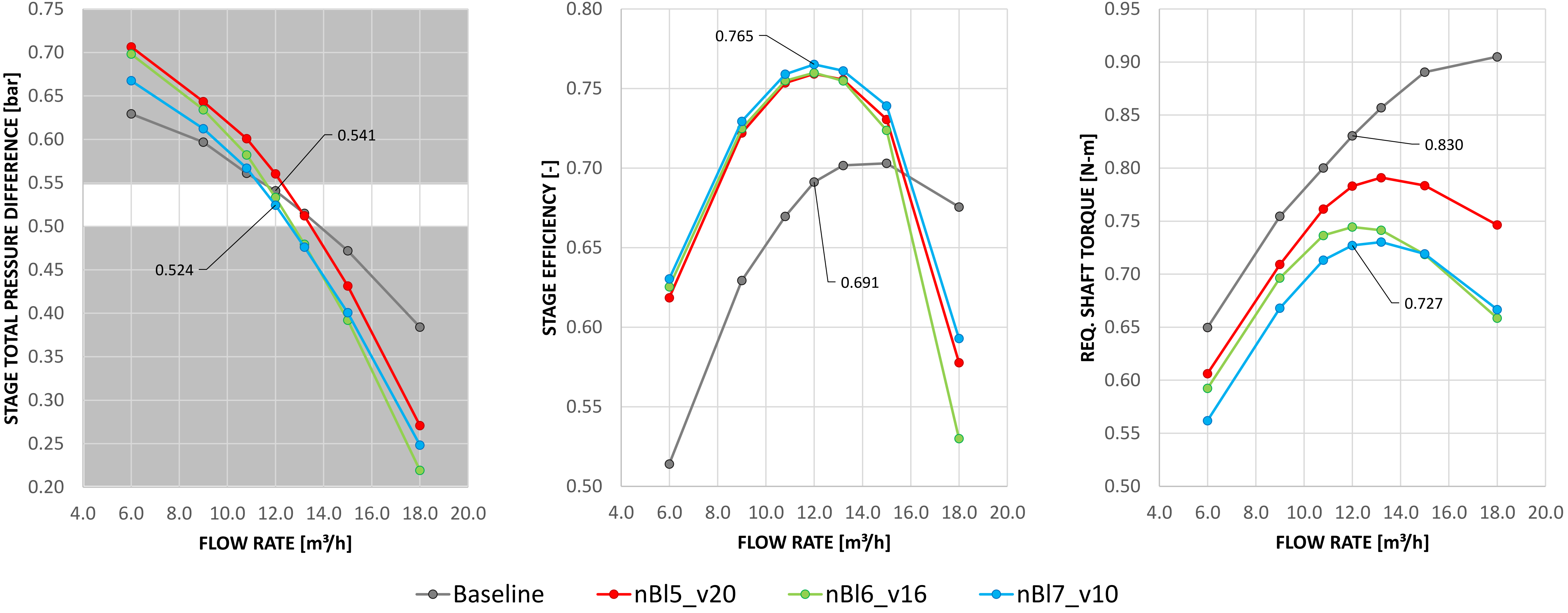
4 Project examples ❶ Centrifugal pump optimization

Results of **final transient simulations**

Stage tot. pressure diff. within target

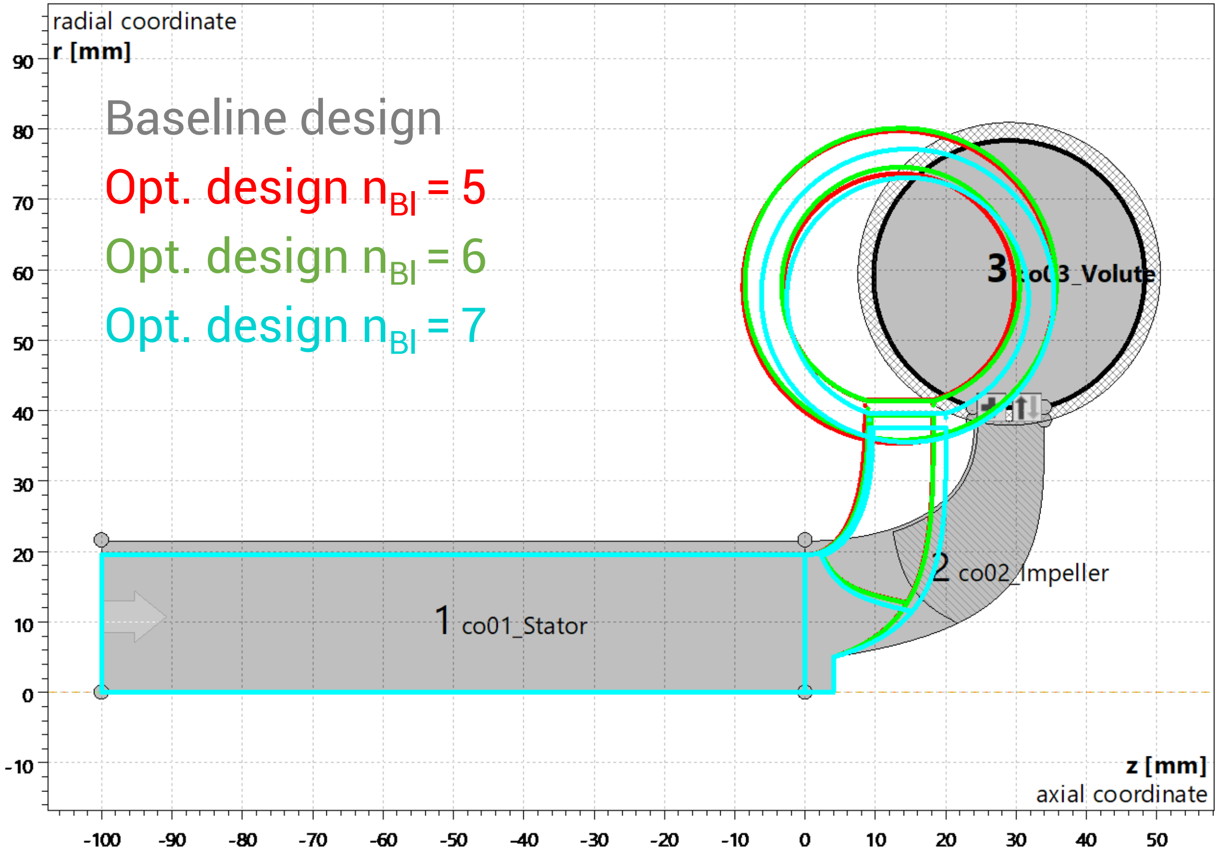
Stage efficiency **increased by 7.4 %**

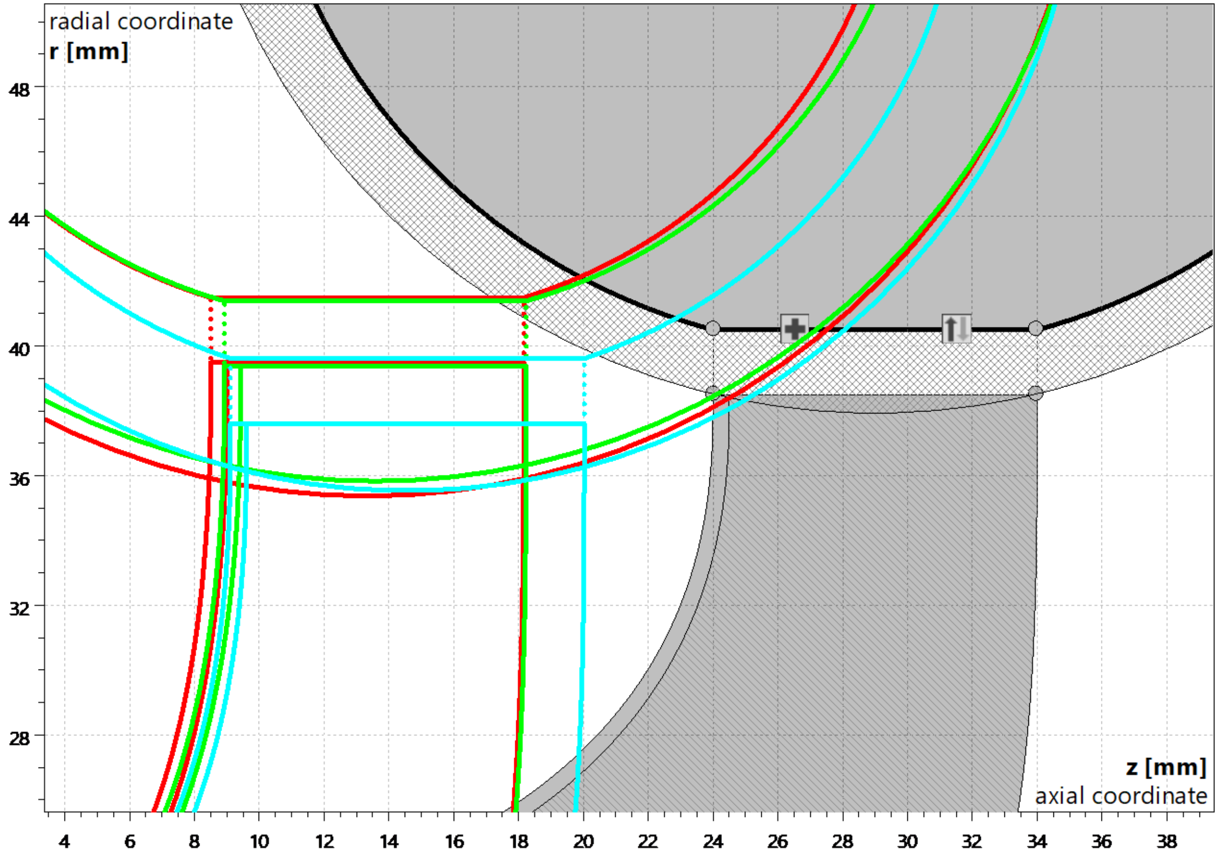
Req. shaft torque **lowered by 12.4 %**



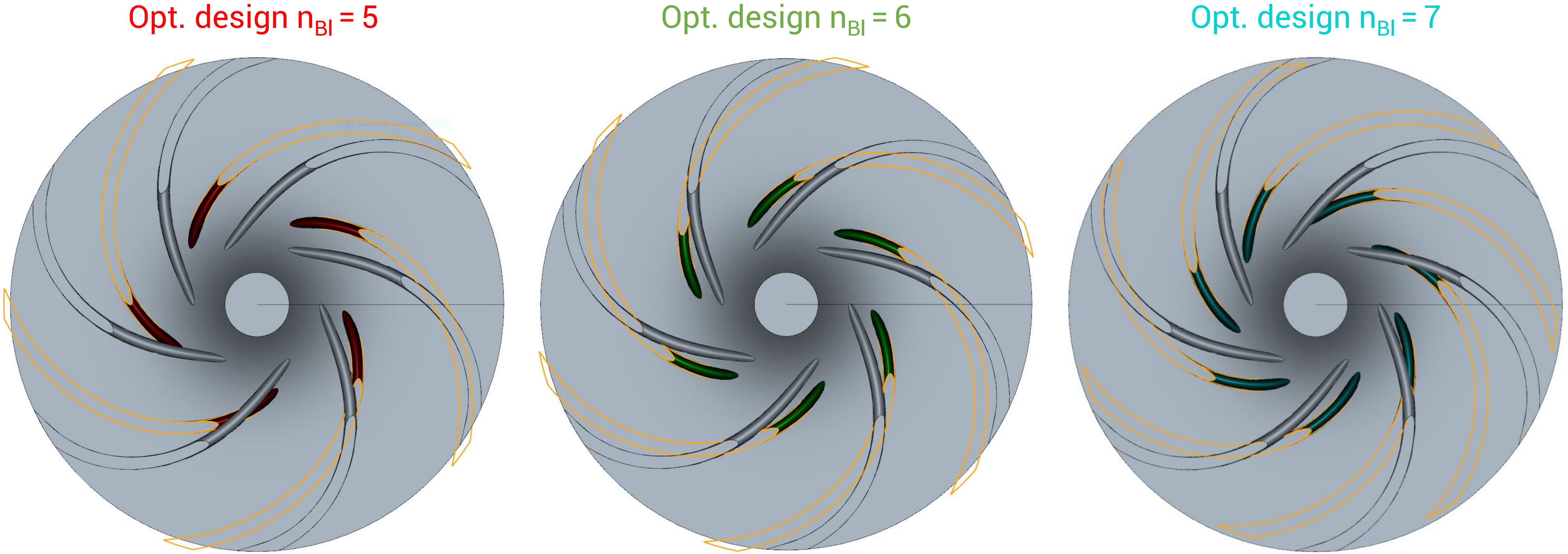
❶ Centrifugal pump optimization

- Improved designs tend to lower axial extension Δz and lower impeller suction diameter d_S
- $n_{Bl} = 5$, $n_{Bl} = 6$ designs tend towards larger impeller diameter d_2 with reduced width b_2
  $n_{Bl} = 7$ design with smaller impeller diameter d_2 and increased width b_2

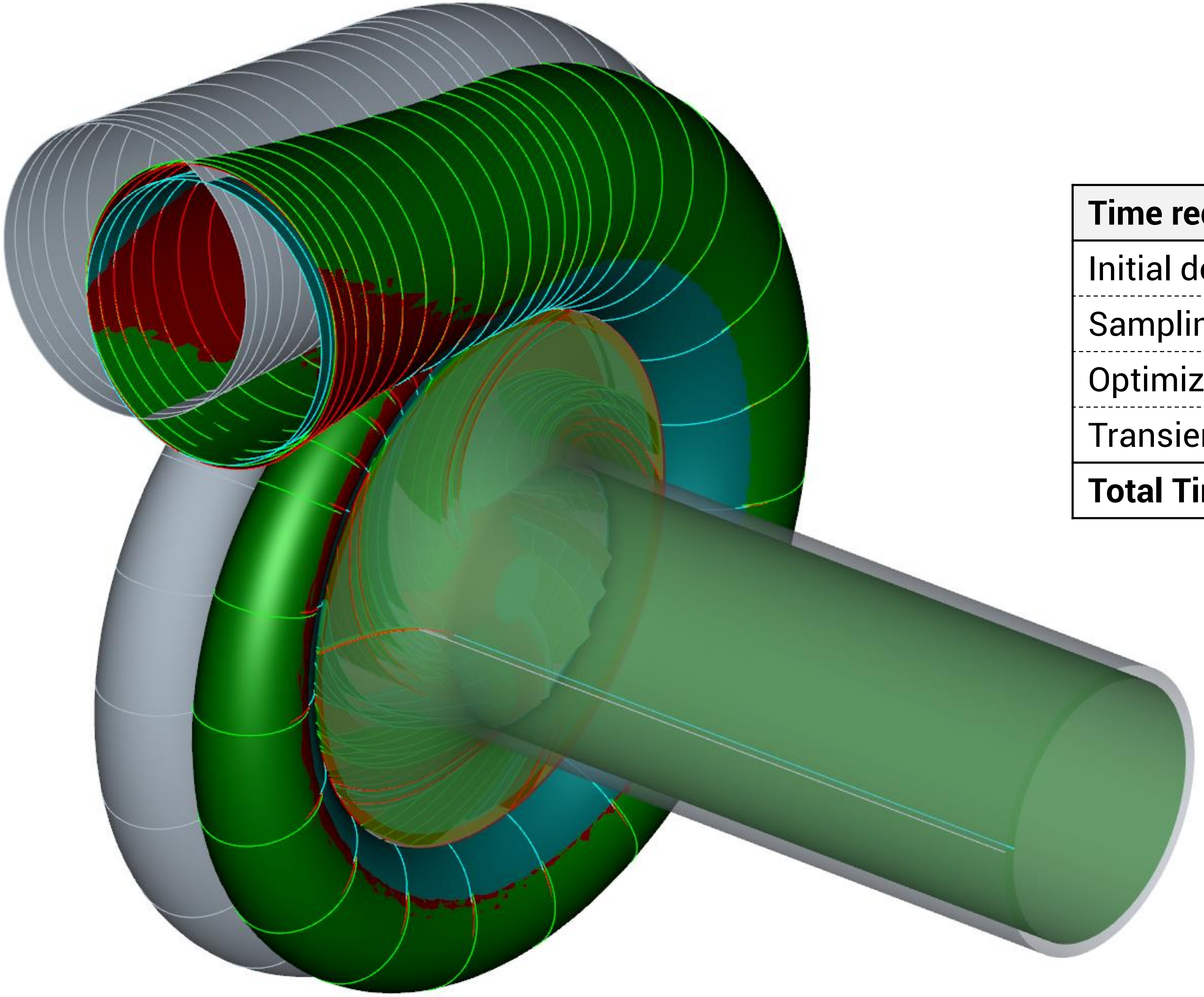




- Improved designs tend to higher blade wrap angle Δφ and higher trailing edge blade angles $\beta_{B2,H}$
- $n_{Bl} = 5$, $n_{Bl} = 6$ designs tend towards larger impeller diameter d_2
  $n_{Bl} = 7$ design with smaller impeller diameter d_2



4 Project examples ❶ Centrifugal pump optimization



Time required	
Initial design/ Workflow setup	1 h
Sampling (200 samples)	12 h
Optimization (60 designs)	6 h
Transient speed-lines (4 x 7 points)	18 h
Total Time	**37 h**

Topics

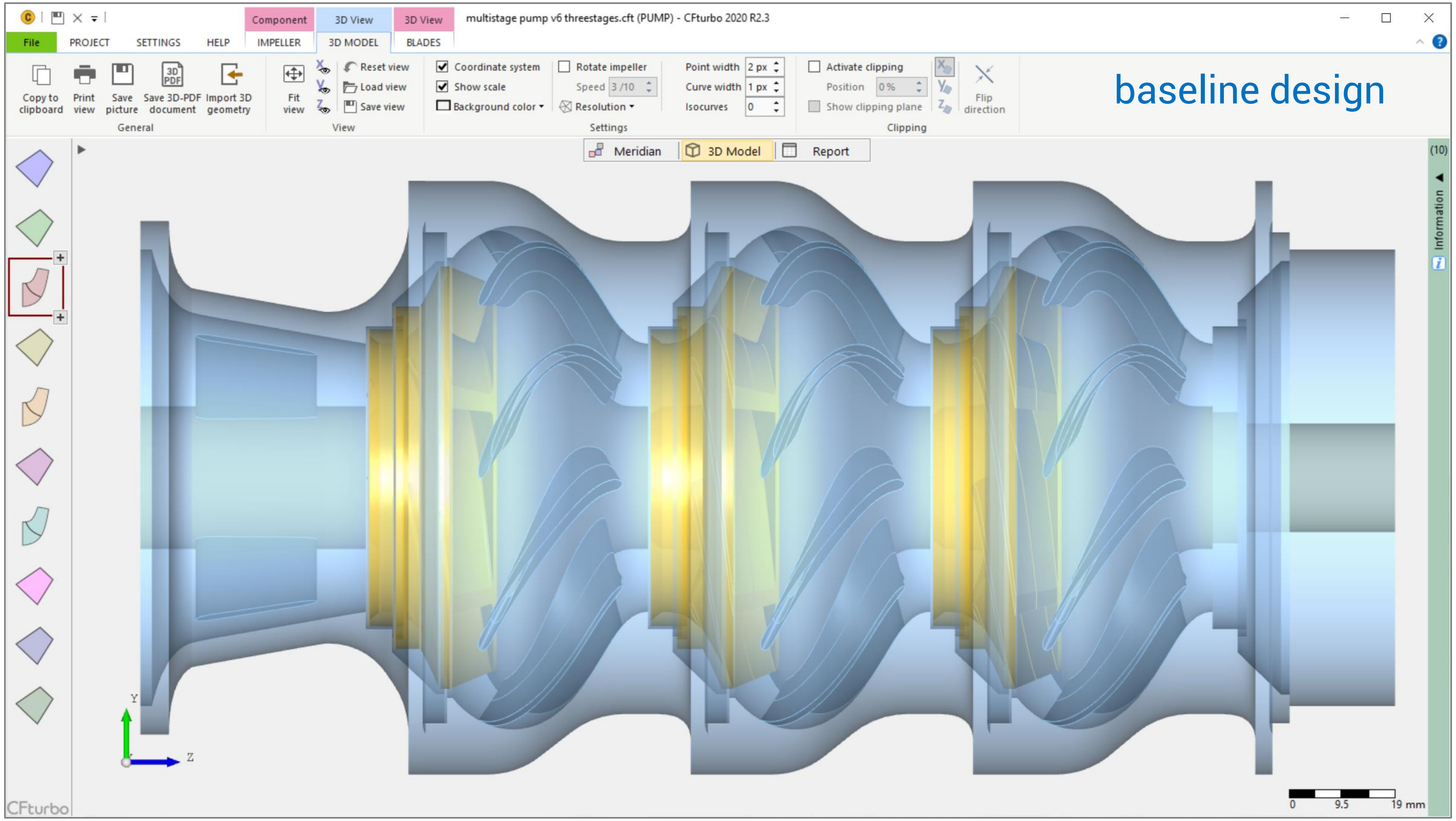
4 Project examples ❷ Multistage pump optimization

Baseline design

- Initial design in CFturbo
- 3D-CFD simulations
- Ansys CFX, Simerics MP
- Steady state and transient

➢ Impeller efficiency 92%

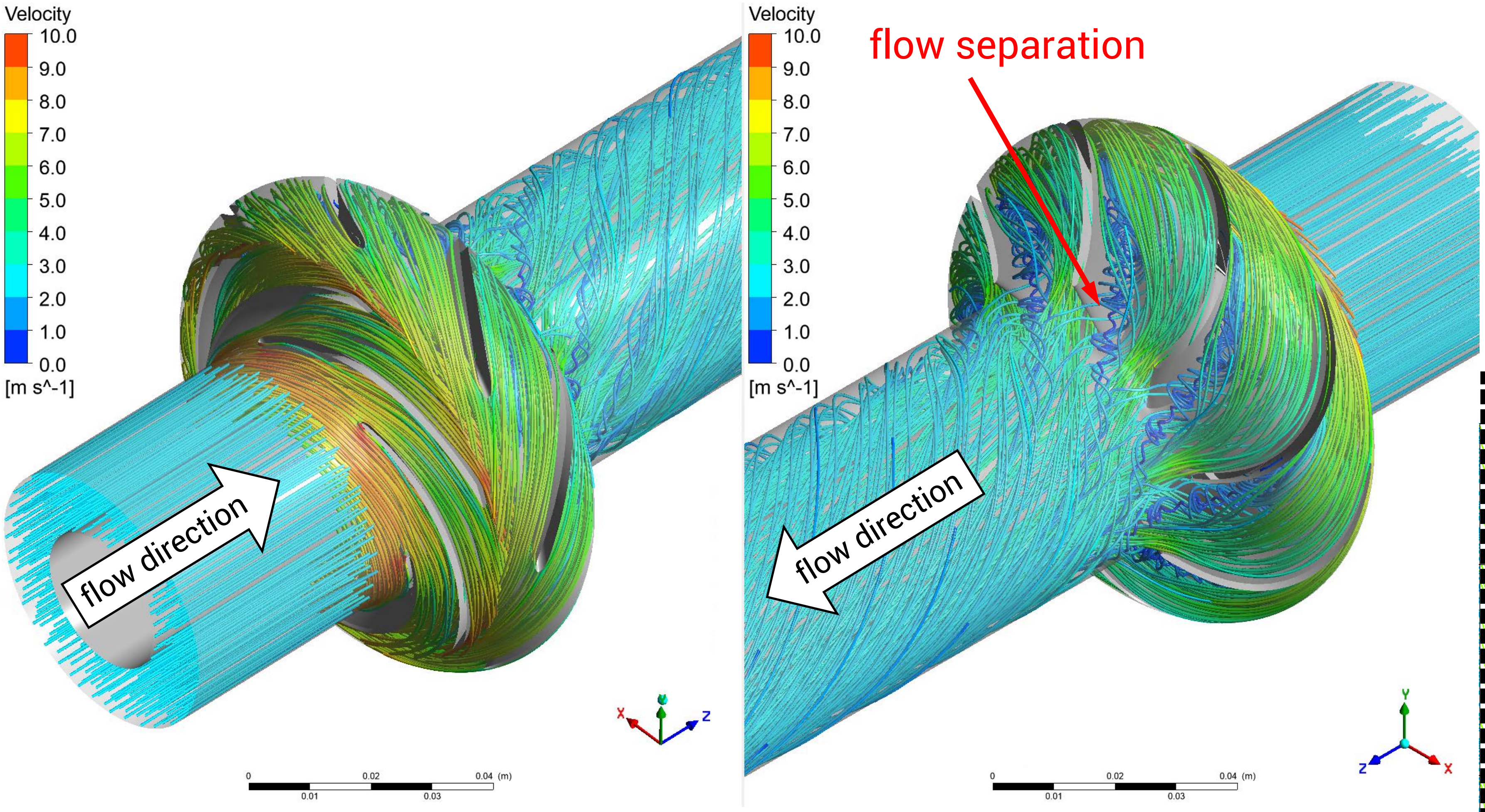
➢ Stage efficiencies 80…82%



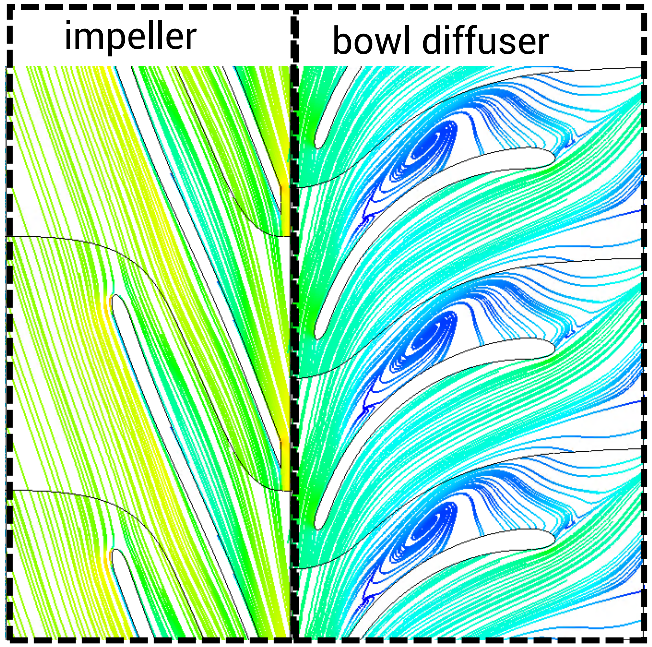
multistage pump v6 threestages.cft (PUMP) - CFturbo 2020 R2.3

☑ Coordinate system
☑ Show scale
☐ Background color
☐ Rotate impeller
Speed 3 /10
Point width 2 px
Curve width 1 px
Isocurves 0
☐ Activate clipping
Position 0%
☐ Show clipping plane

Bowl diffuser optimization – Flow separation inside the bowl diffuser can be observed for baseline design



Blade-to-blade view at mid-span

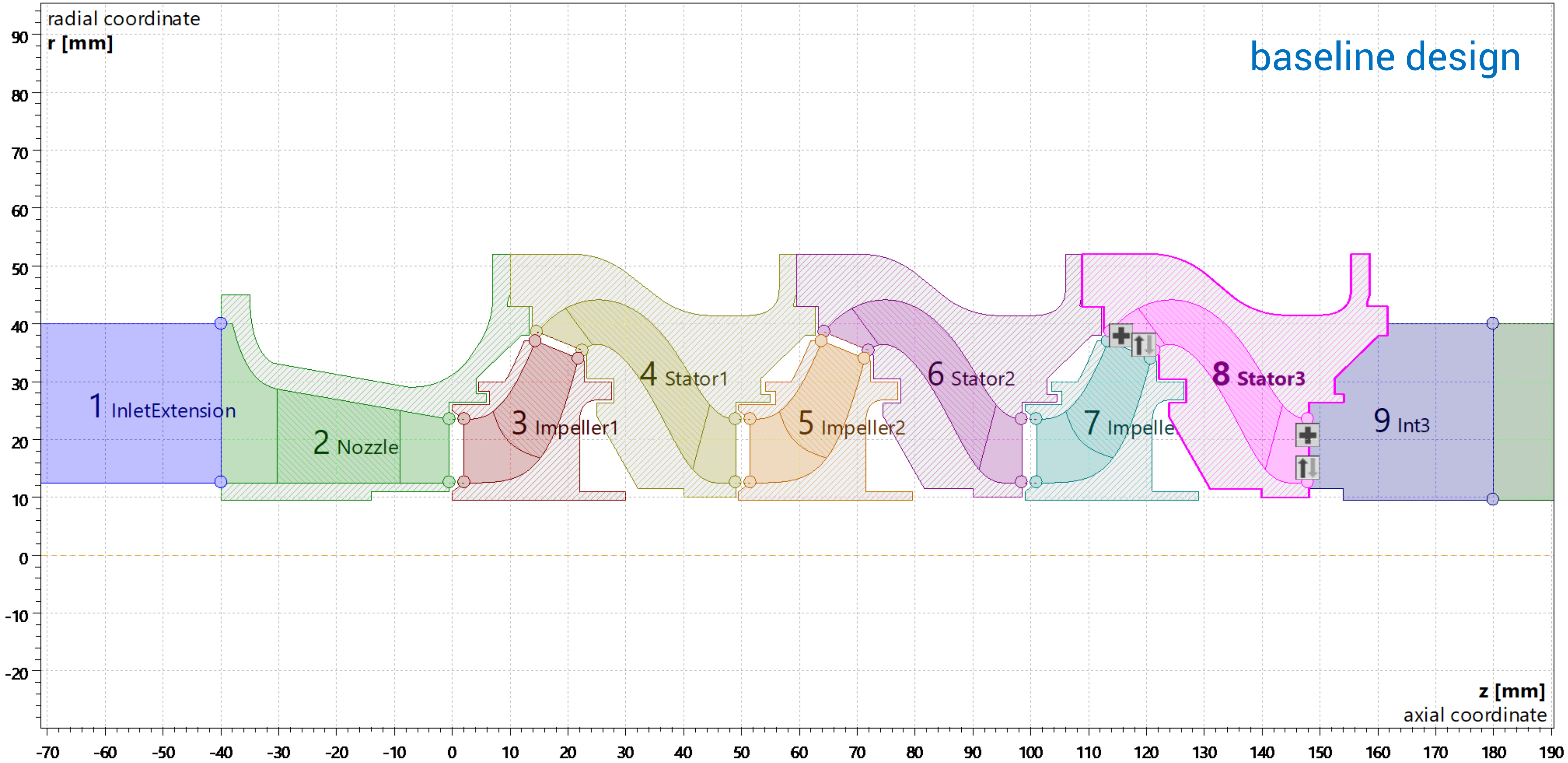


❷ Multistage pump optimization

Objectives

a) Minimize total pressure losses inside the bowl diffusers to improve overall pump efficiency

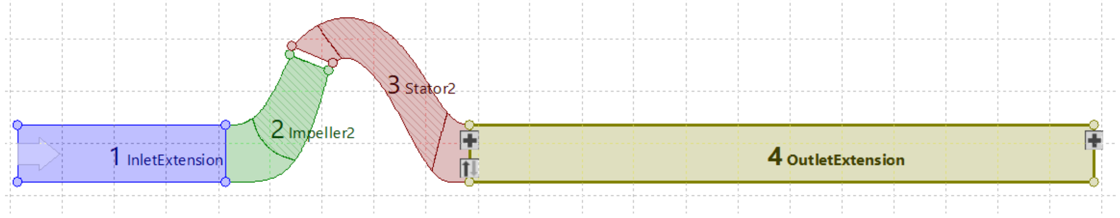
b) Reduce $NPSH_R$ by optimizing impeller design of the first stage



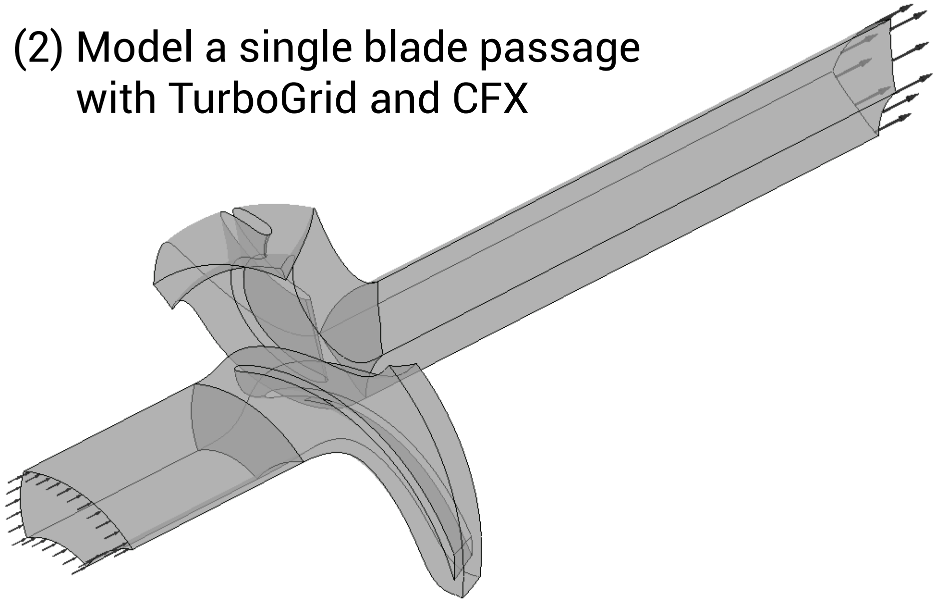
a) Bowl diffuser optimization – Workflow

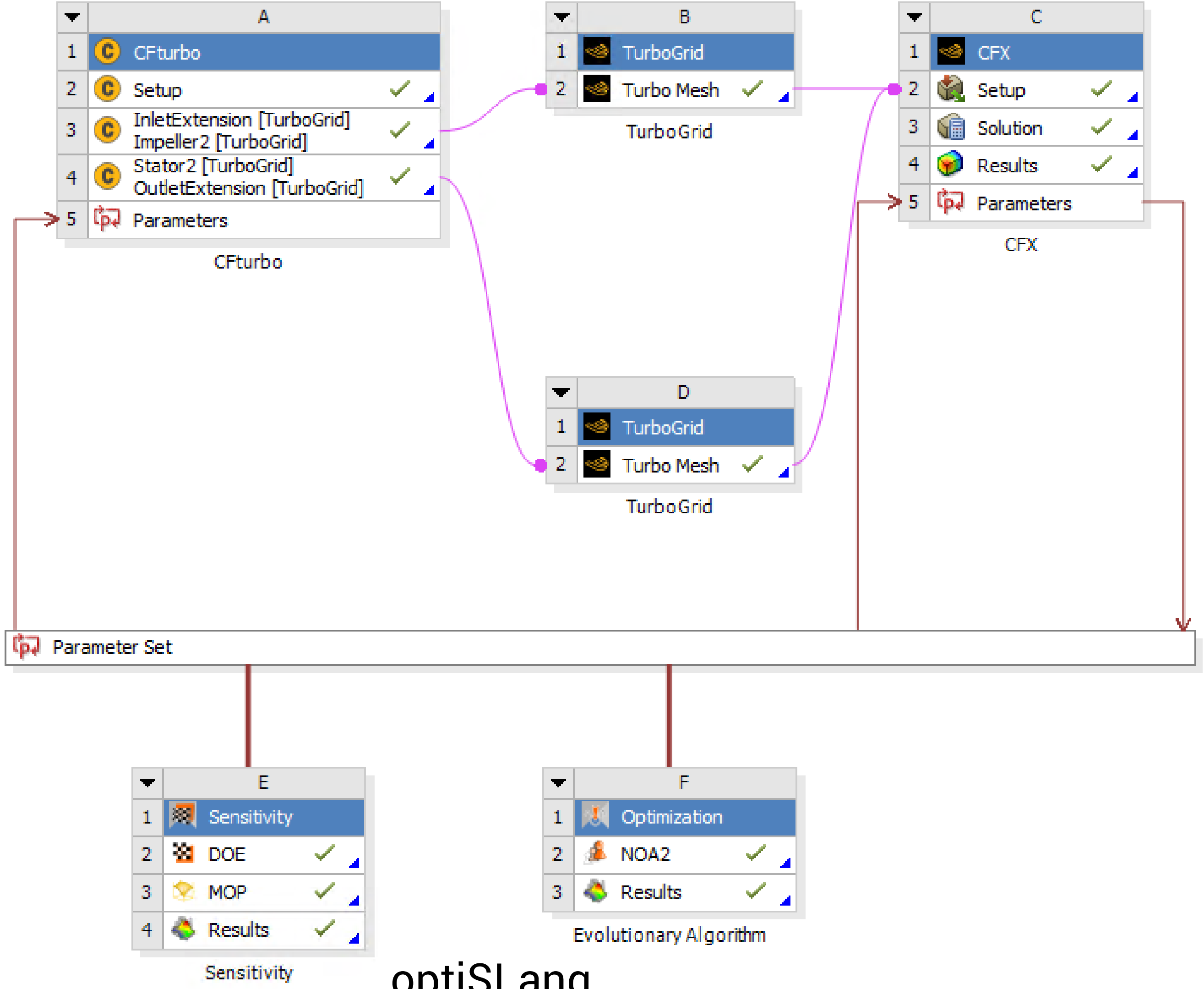
Reduce computational costs of CFD:

(1) Reduce CFturbo model to a single pump stage



(2) Model a single blade passage
with TurboGrid and CFX





	A
1	CFturbo
2	Setup ✓
3	InletExtension [TurboGrid] Impeller2 [TurboGrid] ✓
4	Stator2 [TurboGrid] OutletExtension [TurboGrid] ✓
5	Parameters

CFturbo

	B
1	TurboGrid
2	Turbo Mesh ✓

TurboGrid

	C
1	CFX
2	Setup ✓
3	Solution ✓
4	Results ✓
5	Parameters

CFX

	D
1	TurboGrid
2	Turbo Mesh ✓

TurboGrid

Parameter Set

	E
1	Sensitivity
2	DOE ✓
3	MOP ✓
4	Results ✓

Sensitivity

	F
1	Optimization
2	NOA2 ✓
3	Results ✓

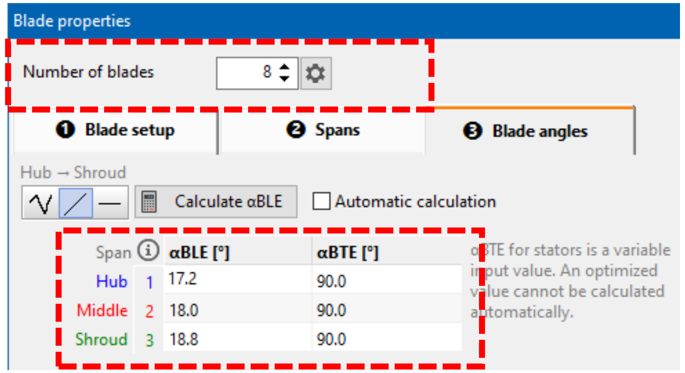
Evolutionary Algorithm

optiSLang

❷ Multistage pump optimization

a) **Bowl diffuser optimization** – Geometry parameters

- Inlet/outlet diameters and axial position is fixed
- Geometry parameters for hub/shroud contour and meridional blade position
- ⇨ 14 geometry parameters for **meridional** design



Blade properties

Number of blades 8

❶ Blade setup ❷ Spans ❸ Blade angles

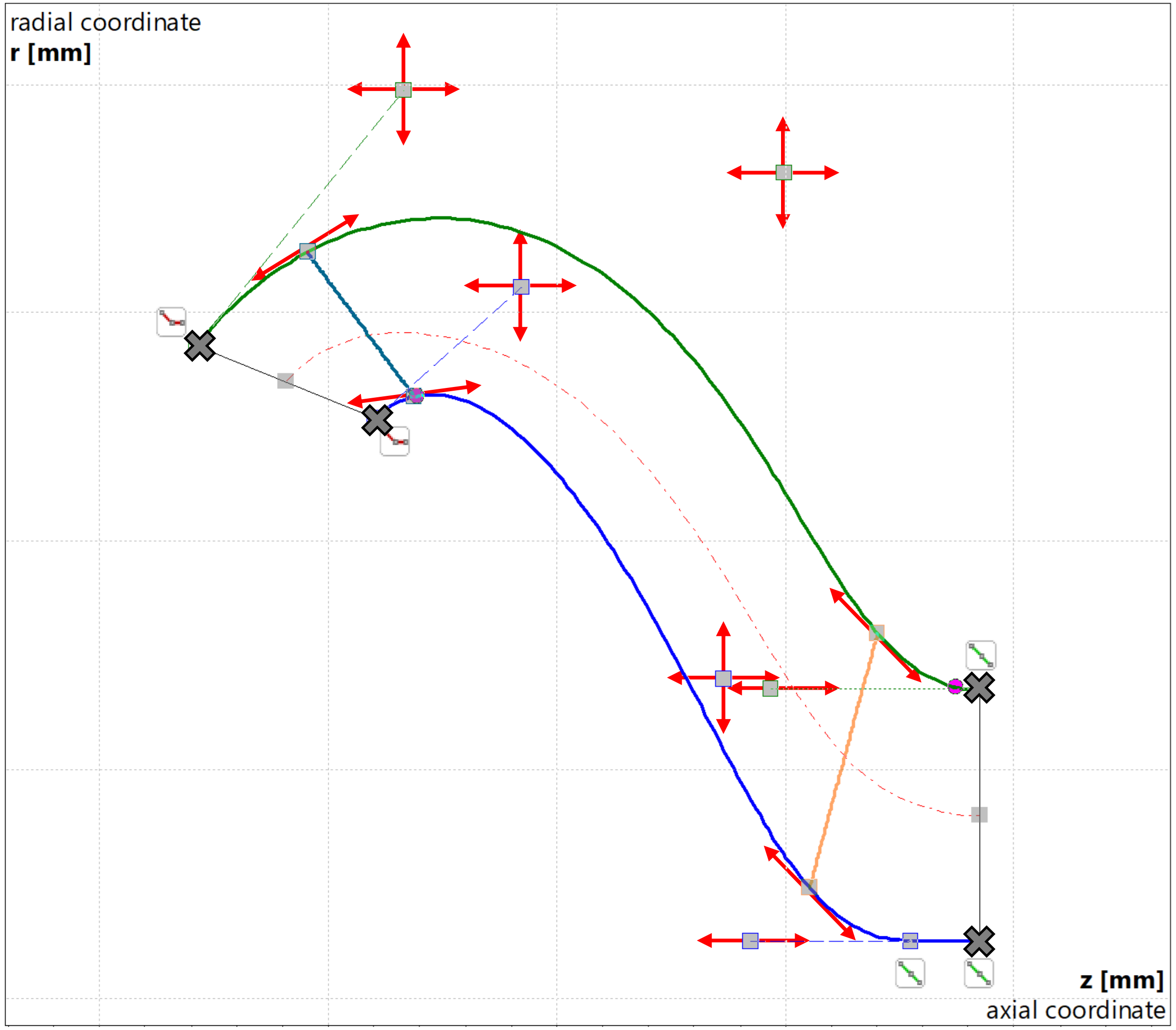
Hub → Shroud

Calculate αBLE ☐ Automatic calculation

Span		αBLE [°]	αBTE [°]
Hub	1	17.2	90.0
Middle	2	18.0	90.0
Shroud	3	18.8	90.0

αBTE for stators is a variable input value. An optimized value cannot be calculated automatically.

- Blade angles defined by 4 geometry parameters
- Number of blades as pre-defined discrete parameter set to avoid unfavorable impeller-stator-interferences
- ⇨ 5 geometry parameters **blade properties**

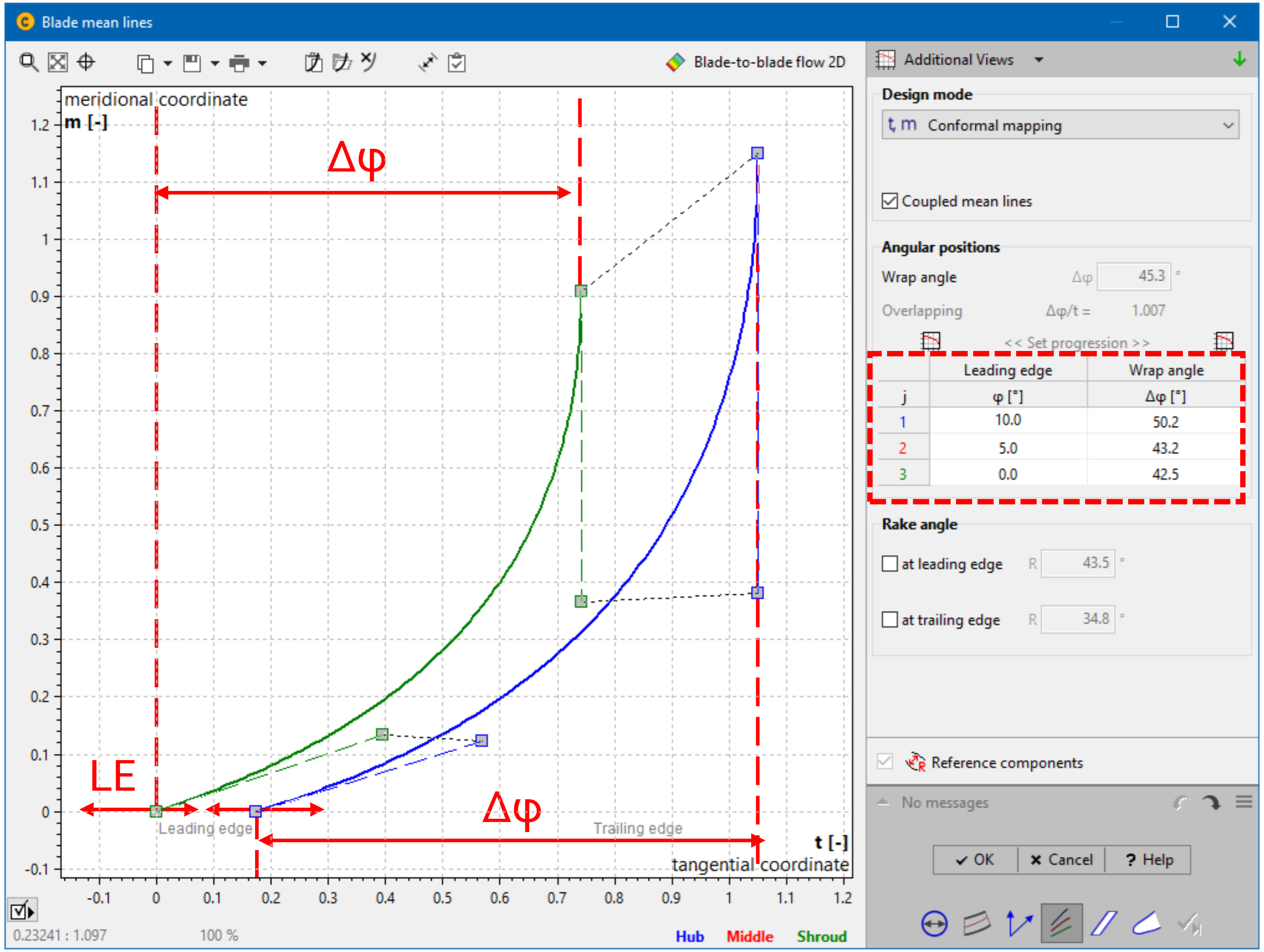


4 Project examples ❷ Multistage pump optimization

a) **Bowl diffuser optimization** – Geometry parameters

- Circumferential leading edge position is defined by 2 parameters
- Blade wrap angle is defined by 2 parameters
- ⇨ 4 geometry parameters **mean line** design

⇨ 23 geometry parameters for bowl diffuser design



Design mode

t, m Conformal mapping

☑ Coupled mean lines

Angular positions

Wrap angle Δφ 45.3 °

Overlapping Δφ/t = 1.007

<< Set progression >>

	Leading edge	Wrap angle
j	φ [°]	Δφ [°]
1	10.0	50.2
2	5.0	43.2
3	0.0	42.5

Rake angle

☐ at leading edge R 43.5 °

☐ at trailing edge R 34.8 °

☑ Reference components

No messages

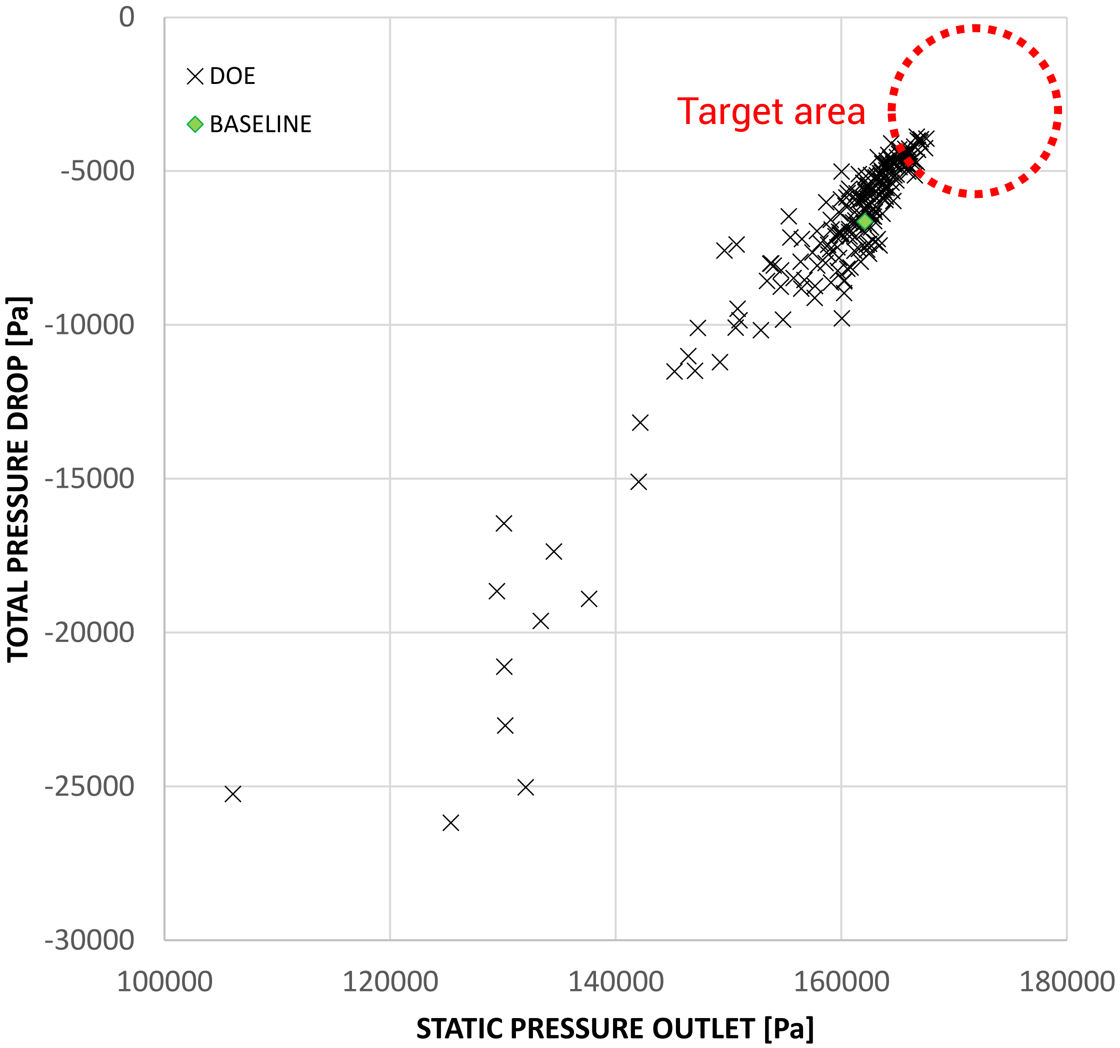
a) Bowl diffuser optimization – Sensitivity analysis (DoE)

Statistics:

- 300 samples by advanced Latin hypercube method
- 20% designs failed in TurboGrid
- 10% designs failed in CFturbo
- 3% designs failed in CFX solver

7 responses from CFD analysis:

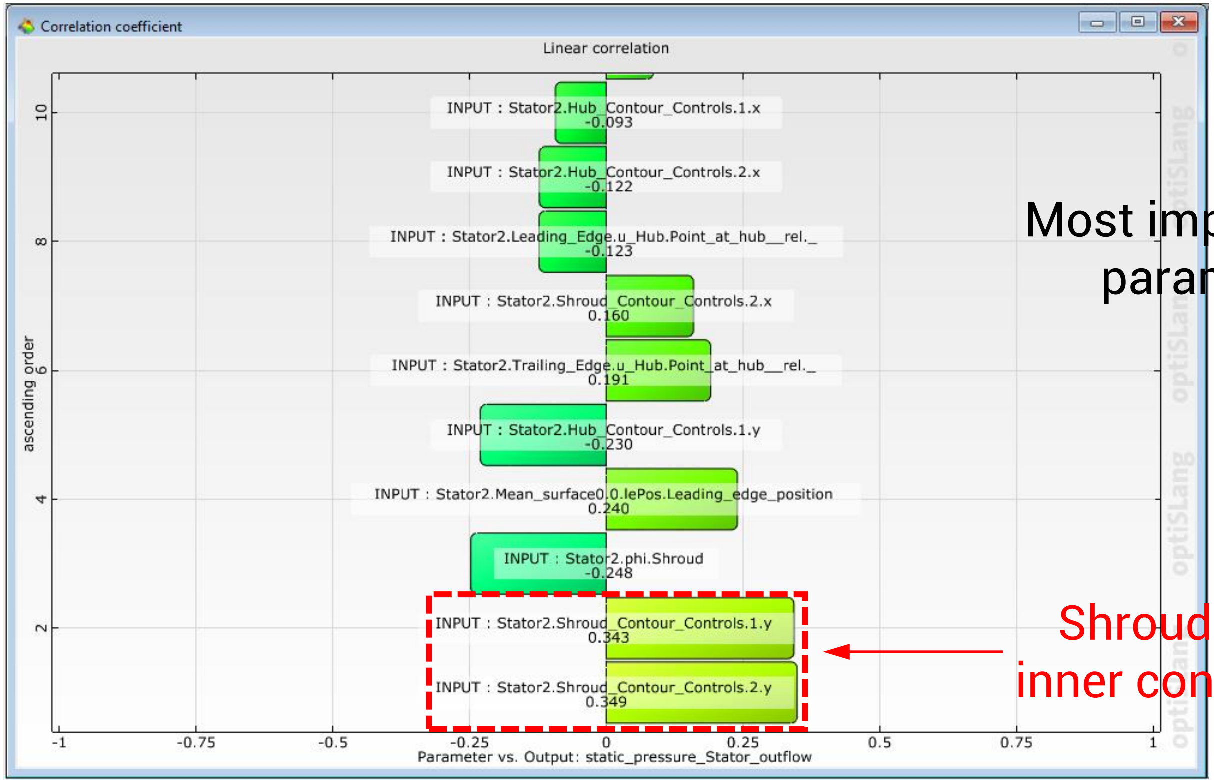
- Total pressure difference, impeller
- Total pressure difference, stage
- Efficiency, impeller
- Efficiency, stage
- Shaft power
- Maximize static pressure at bowl diffuser outflow
  = reduce circumferential velocity component
- Minimize total pressure losses in bowl diffuser
  = reduce flow separation



4 Project examples ❷ Multistage pump optimization

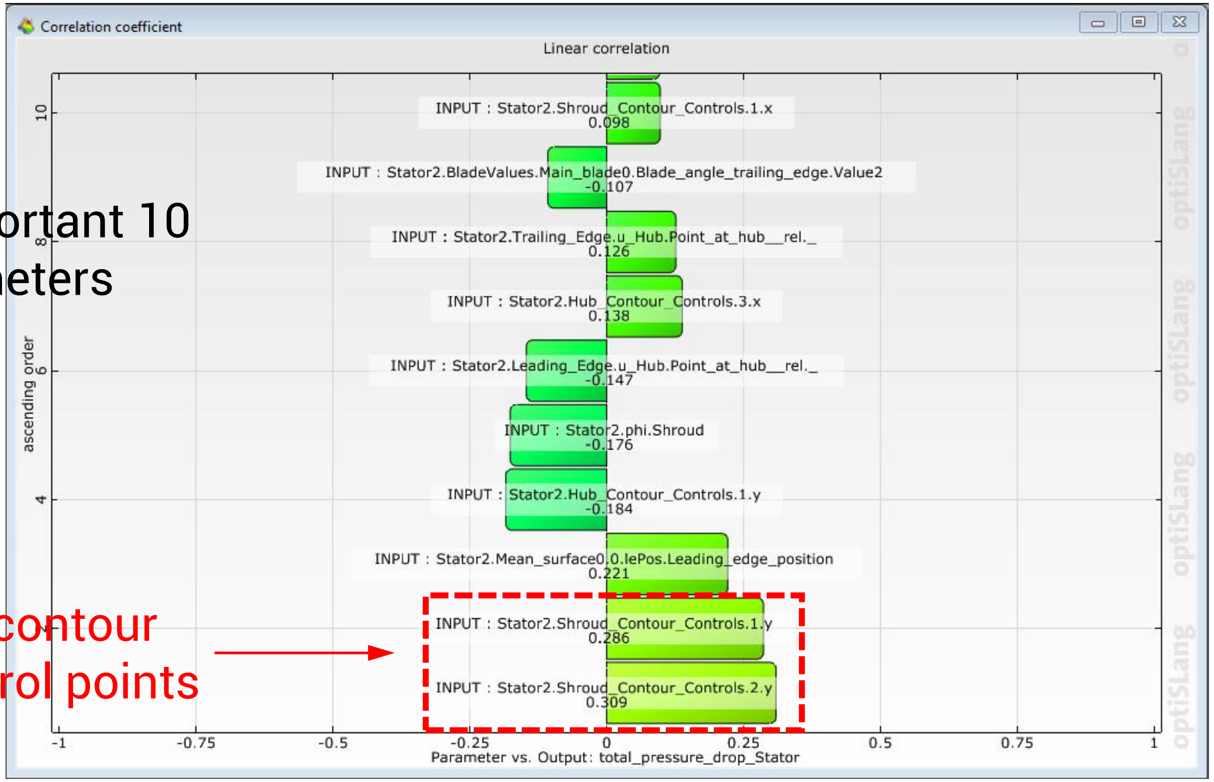
a) **Bowl diffuser optimization** – Sensitivity analysis (DoE)

a) Static pressure bowl diffuser outflow ← Correlation coefficients → b) Total pressure losses bowl diffuser



Most important 10 parameters

Shroud contour inner control points



a) **Bowl diffuser optimization** – Optimization

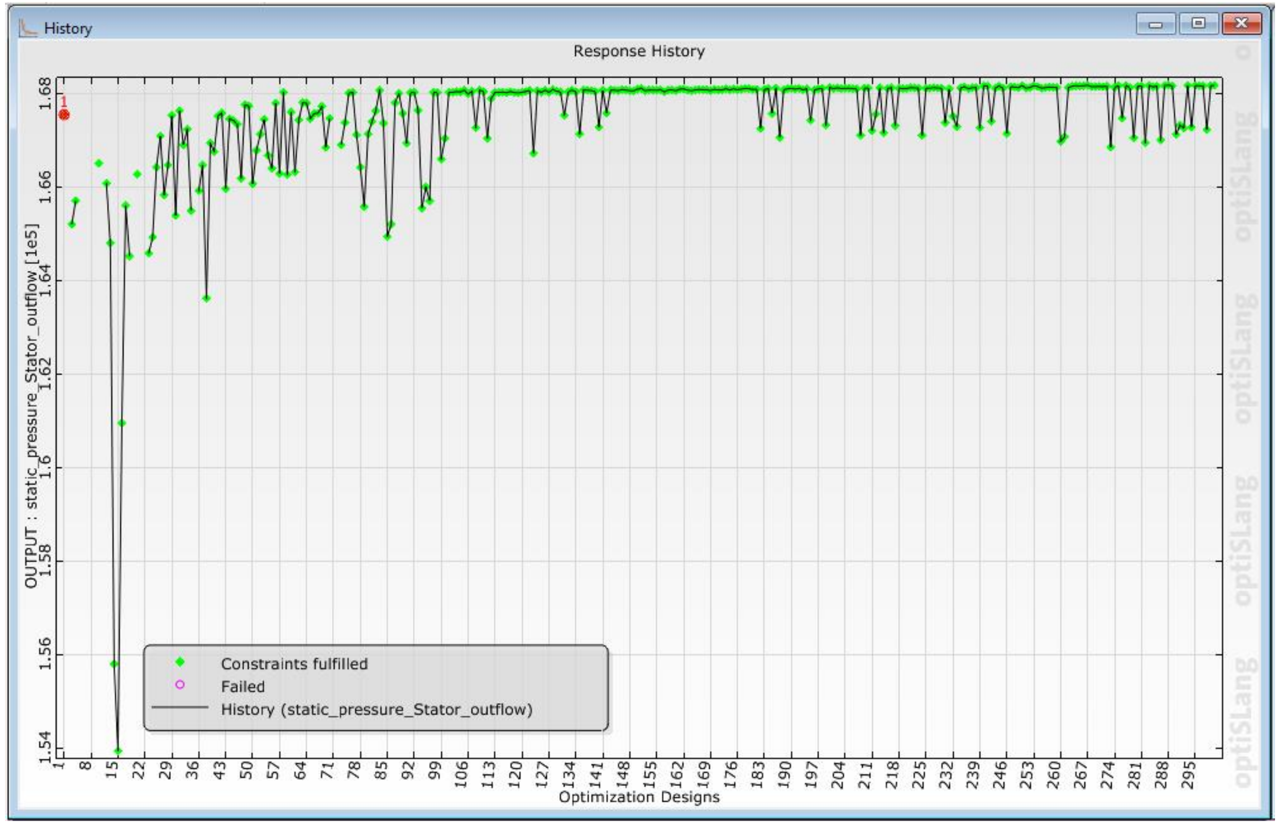
- Evolutionary algorithm based on DoE
- Parameter set reduced from 23 parameters down to 10

- Single objective optimization :

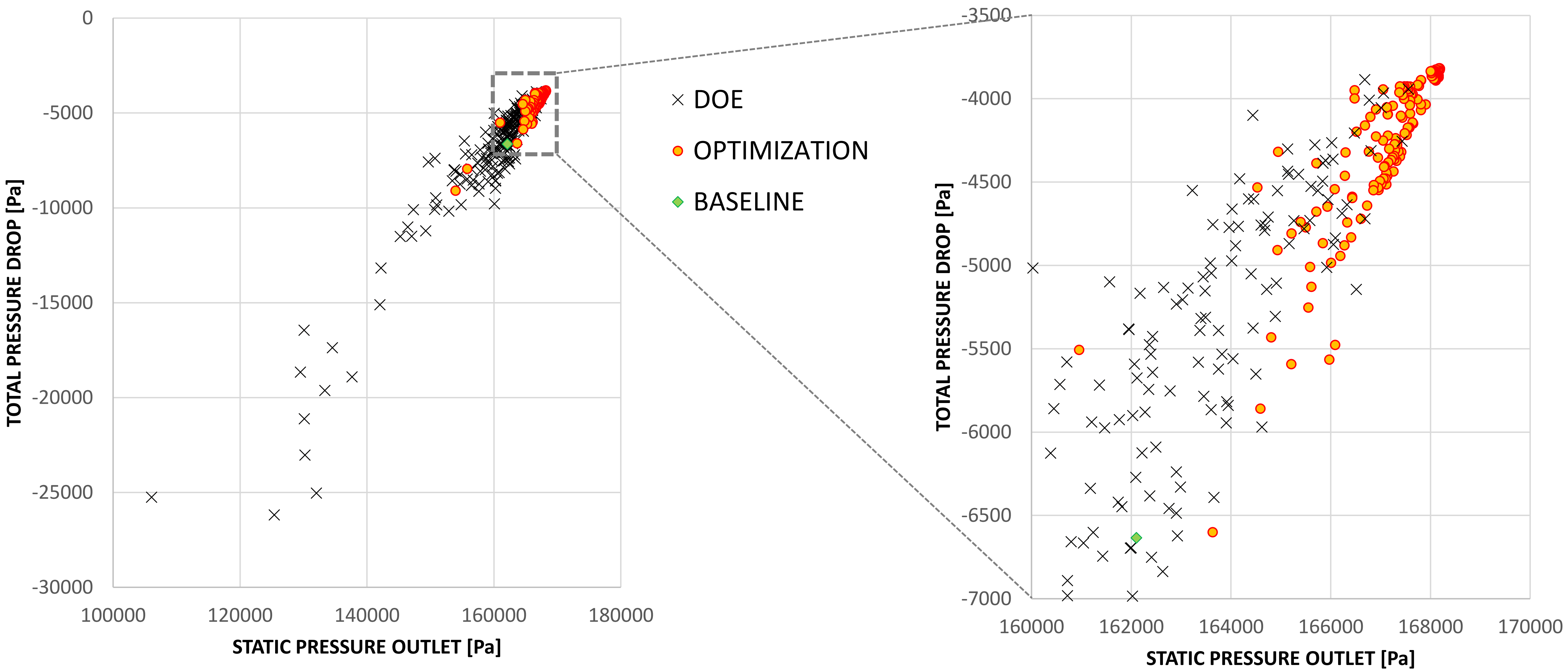
  Maximize static pressure at bowl diffuser outlet
  - by reducing internal pressure losses
  - by reducing flow swirl at outlet

- Statistics:
  - 300 designs were created
  - 4% of the created designs failed (~80% TurboGrid, ~10% CFturbo, ~10% CFX)

Response history: Static pressure at bowl diffuser outflow



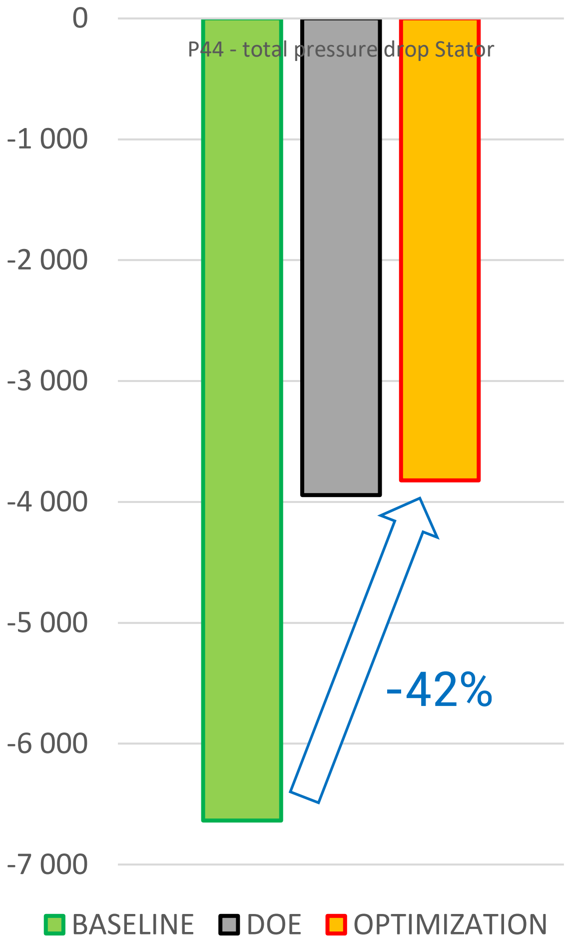
a) Bowl diffuser optimization – Optimization



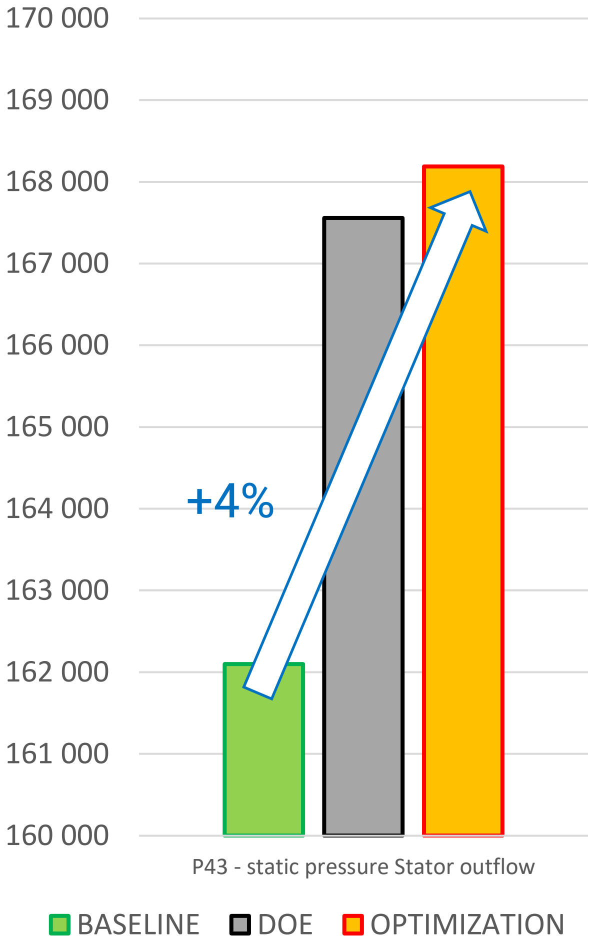
4 Project examples ❷ Multistage pump optimization

a) Bowl diffuser optimization – Optimization

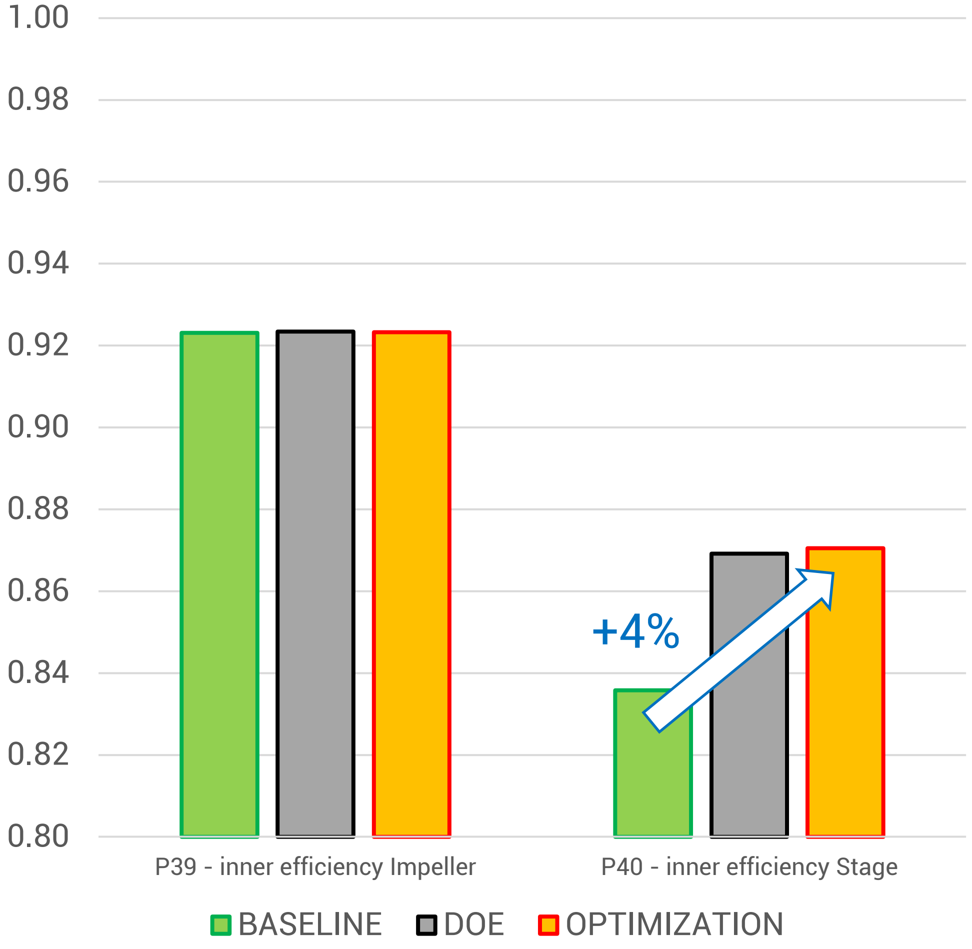
Total pressure losses



Static pressure at outflow



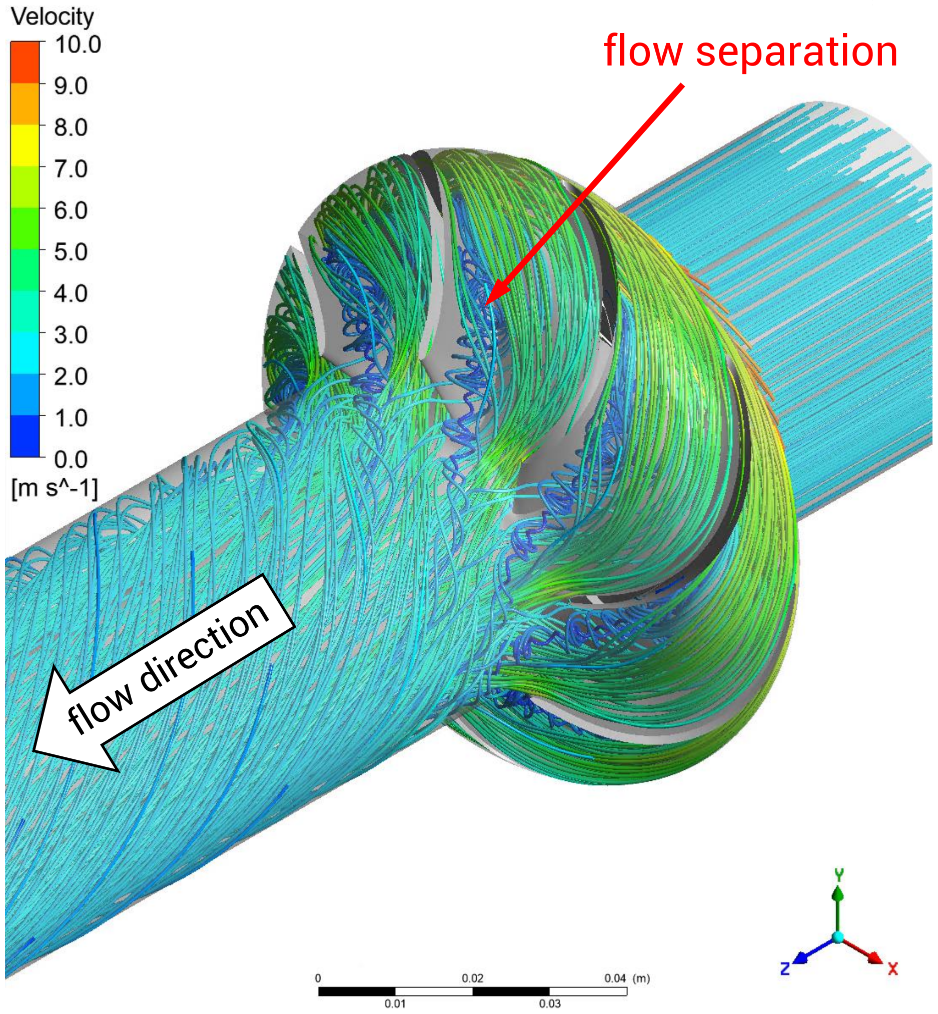
Efficiency



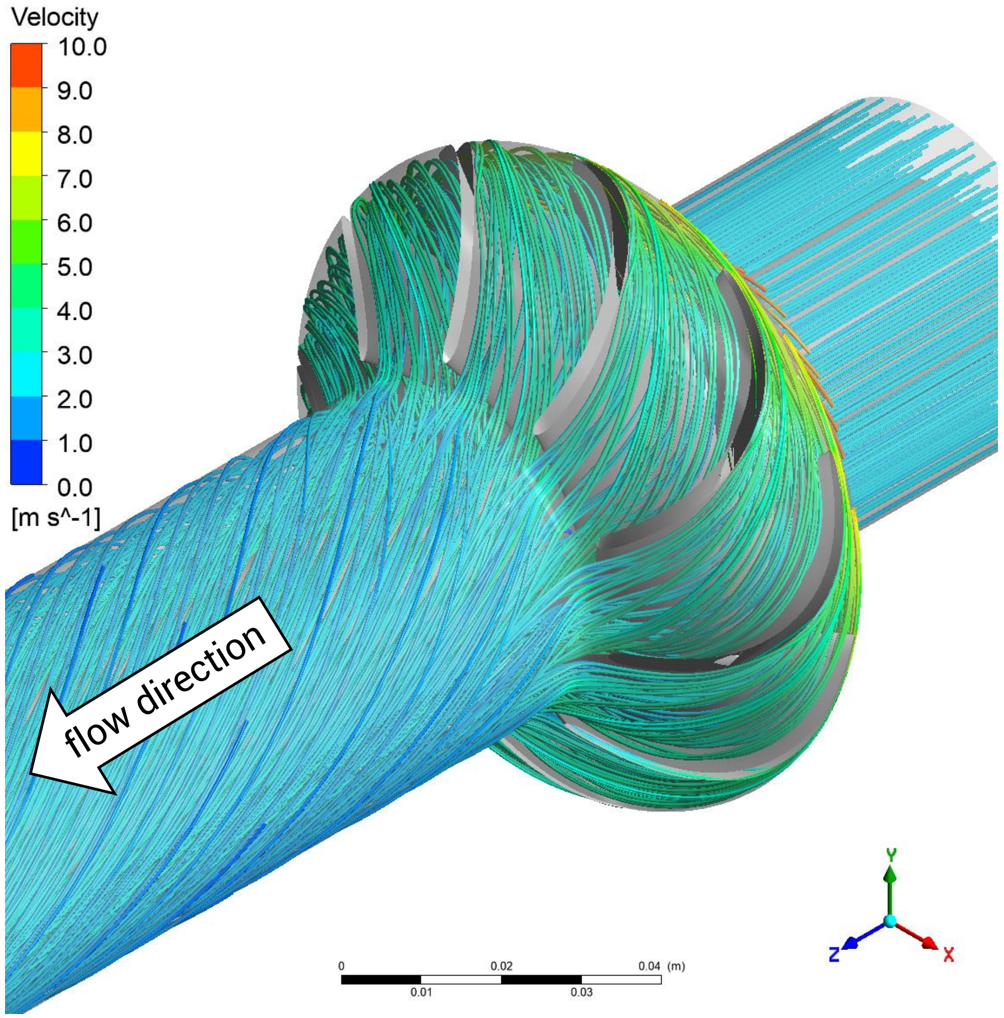
4 Project examples ❷ Multistage pump optimization

a) Bowl diffuser optimization – Optimization

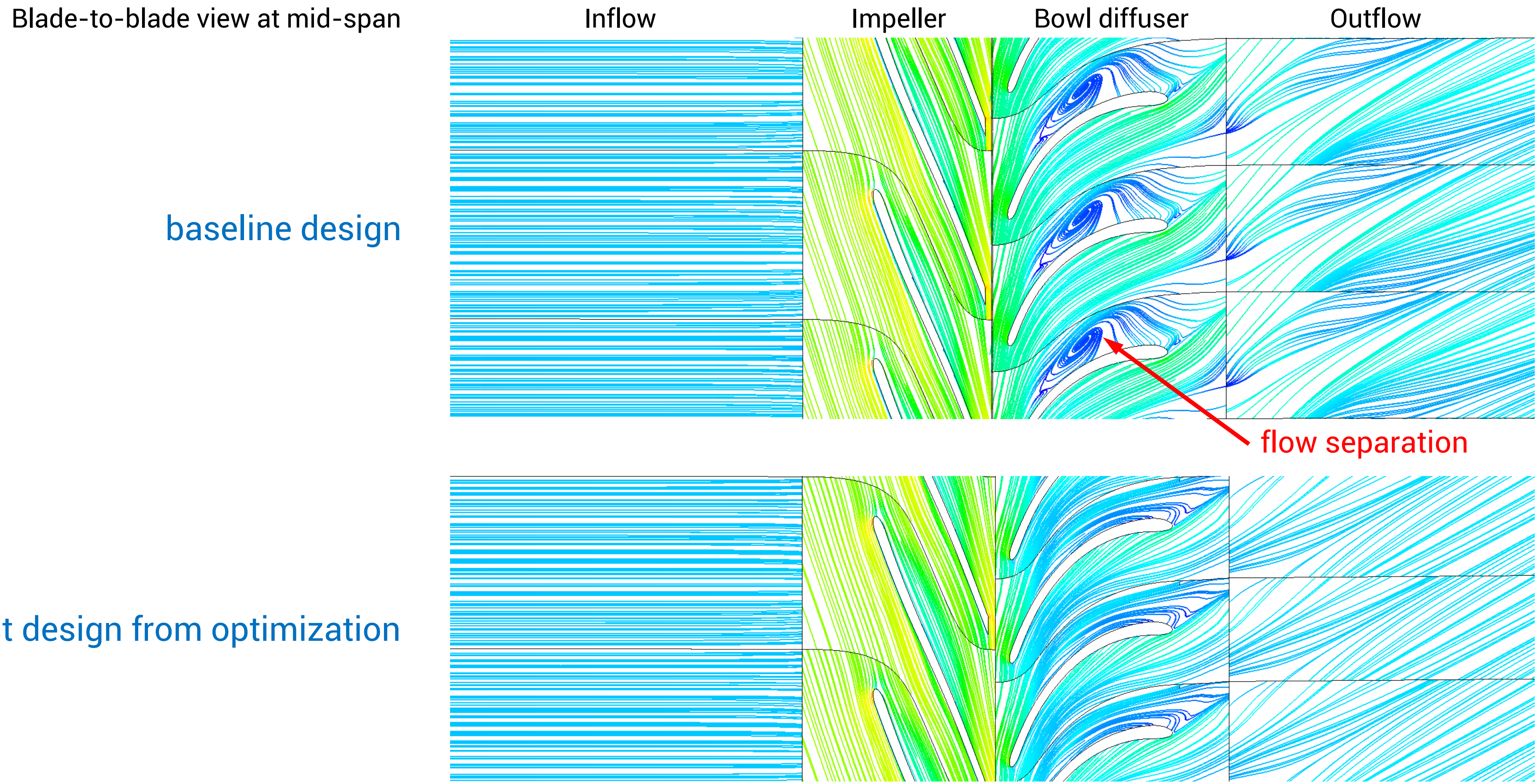
baseline design



best design from optimization



a) Bowl diffuser optimization – Optimization

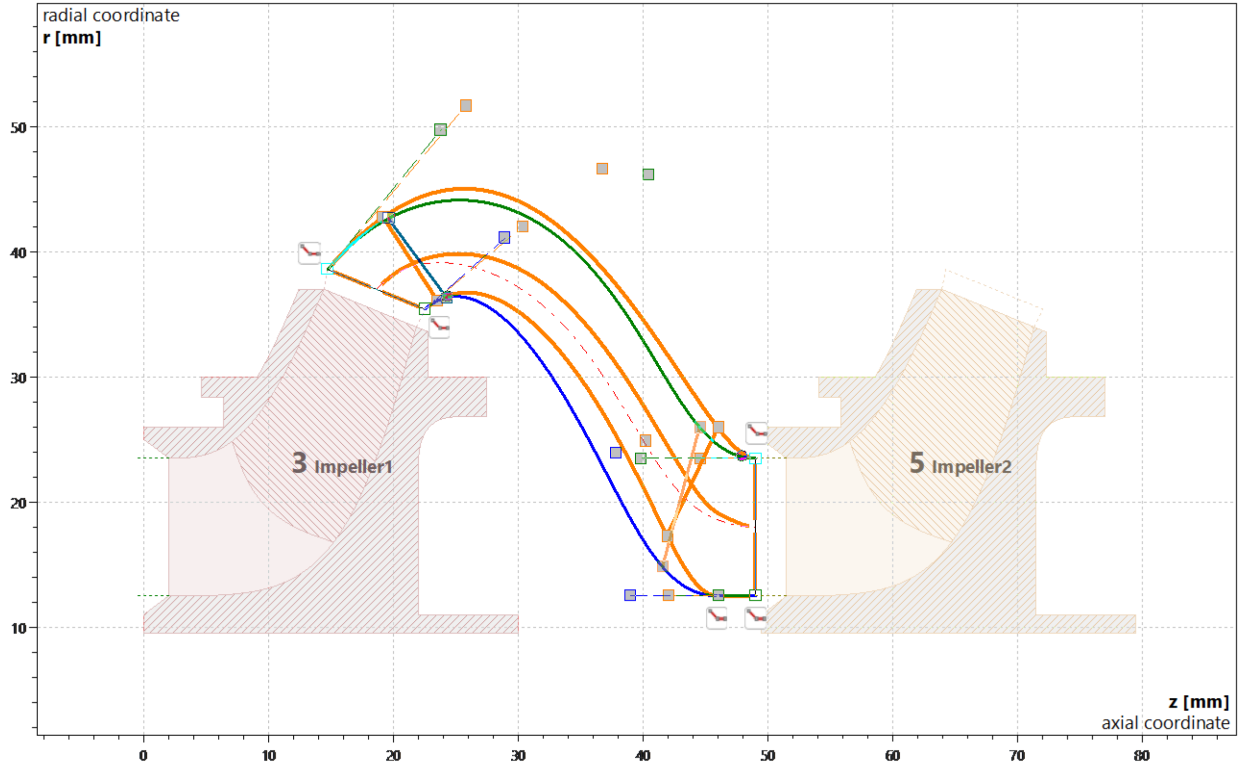


a) Bowl diffuser optimization – Optimization

Best design from optimization with:

- Higher number of blades
- Higher blade lean angle
- Smoother flow redirection in meridional direction

🟩 baseline design
🟧 best design from optimization

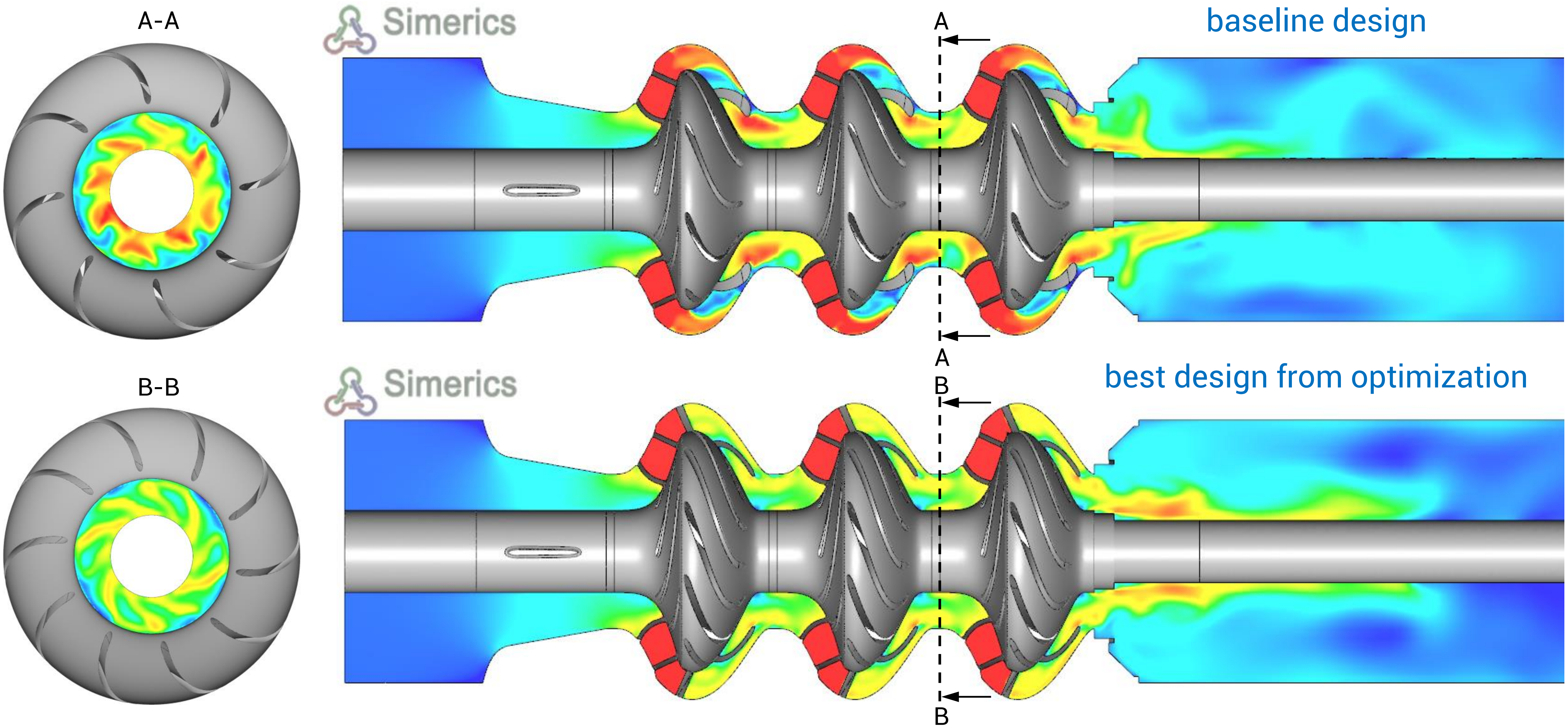


4 Project examples

❷ Multistage pump optimization

a) Bowl diffuser optimization – Transient CFD for 360° multistage model

Flow: Velocity magnitude [m/s]
0 5



b) NPSH$_R$ optimization of first impeller – Objectives

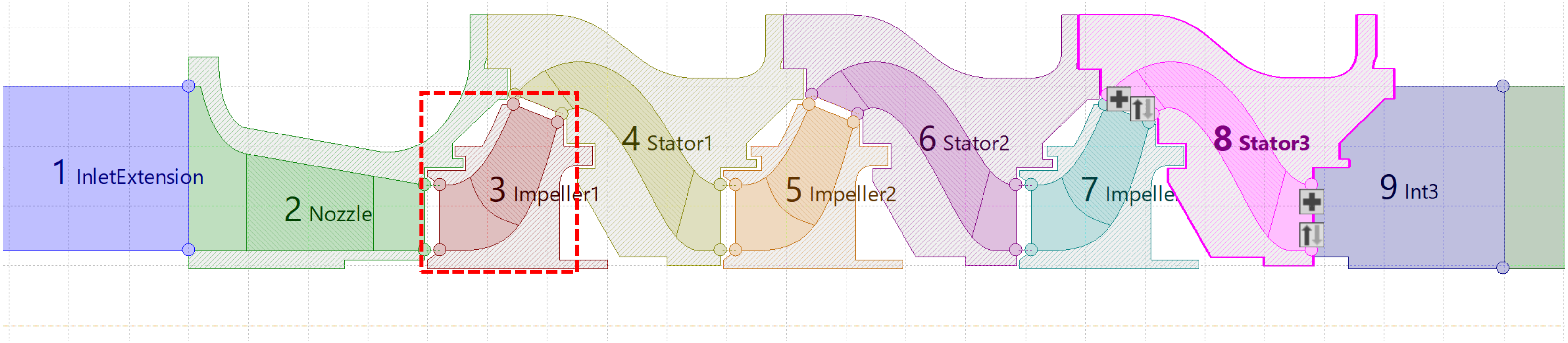
Reduce NPSH$_{R,3}$ of the first pump stage while maintaining a **high impeller efficiency**

⇨ Perform an optimization with multiple objectives:

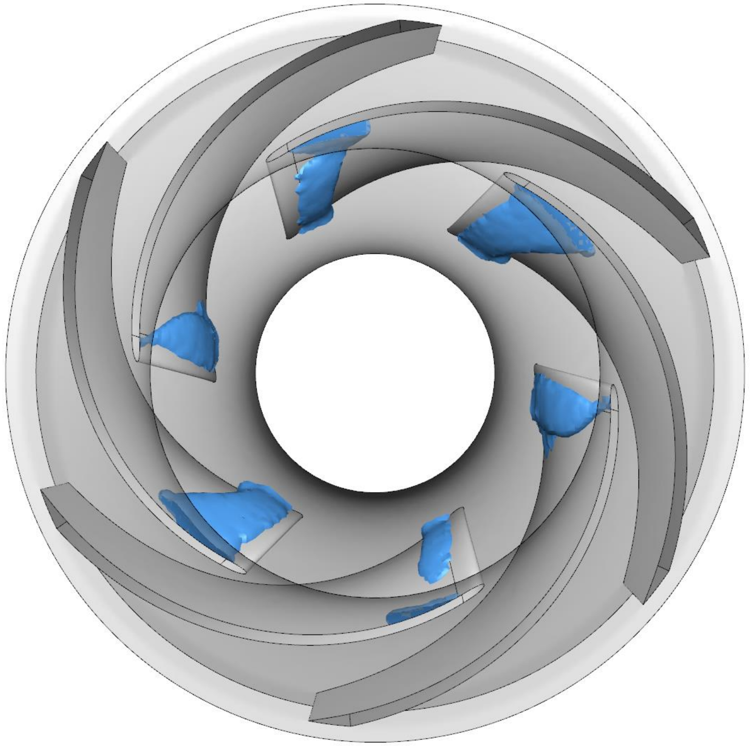
(1) **Minimize NPSH$_{R,3}$** of impeller (first stage)

(2) **Maximize efficiency** of impeller (first stage)

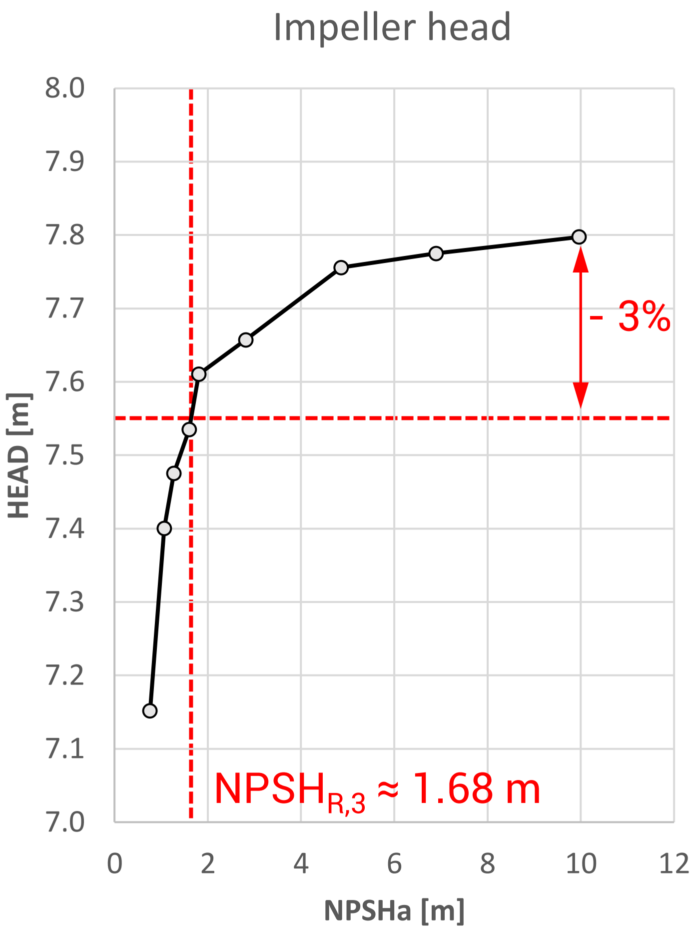
baseline design

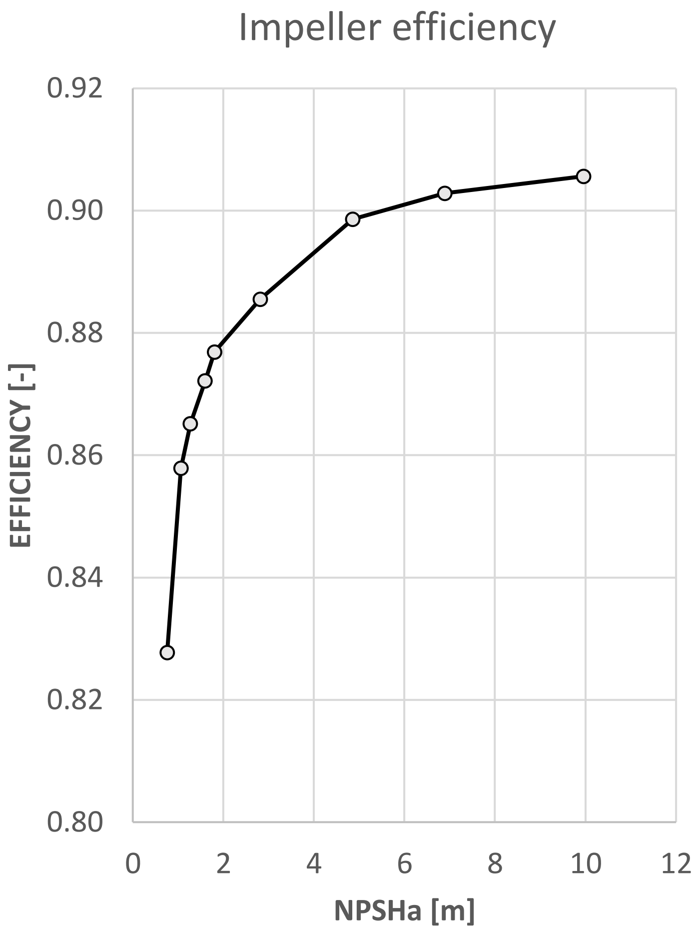


b) $NPSH_R$ optimization of first impeller – Baseline design



Iso-surfaces, vapor volume fraction > 1%

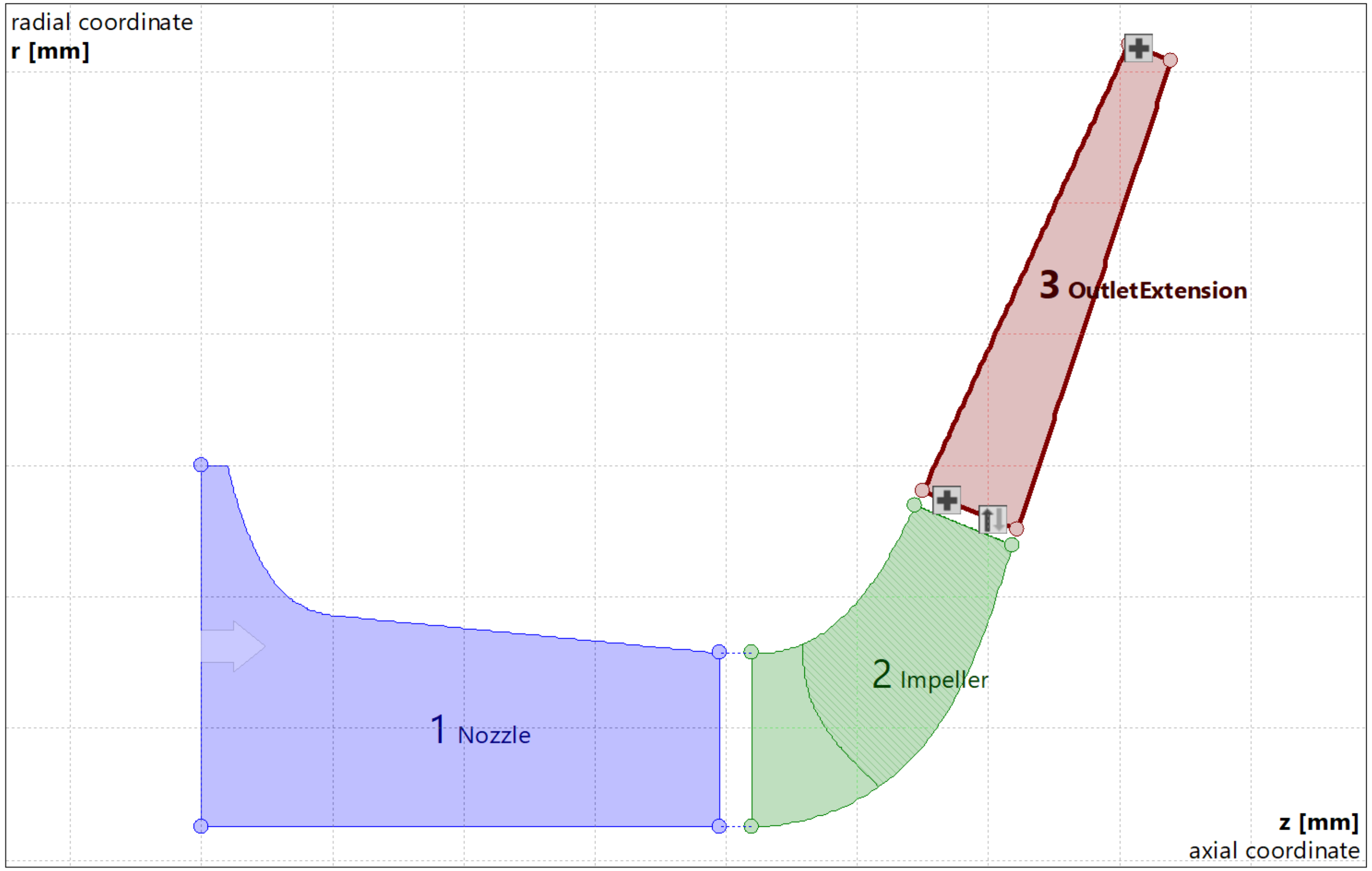




b) $NPSH_R$ optimization of first impeller – Reduced model

Nozzle + Impeller + artificial outlet extension

⇨ keep the computational cost low

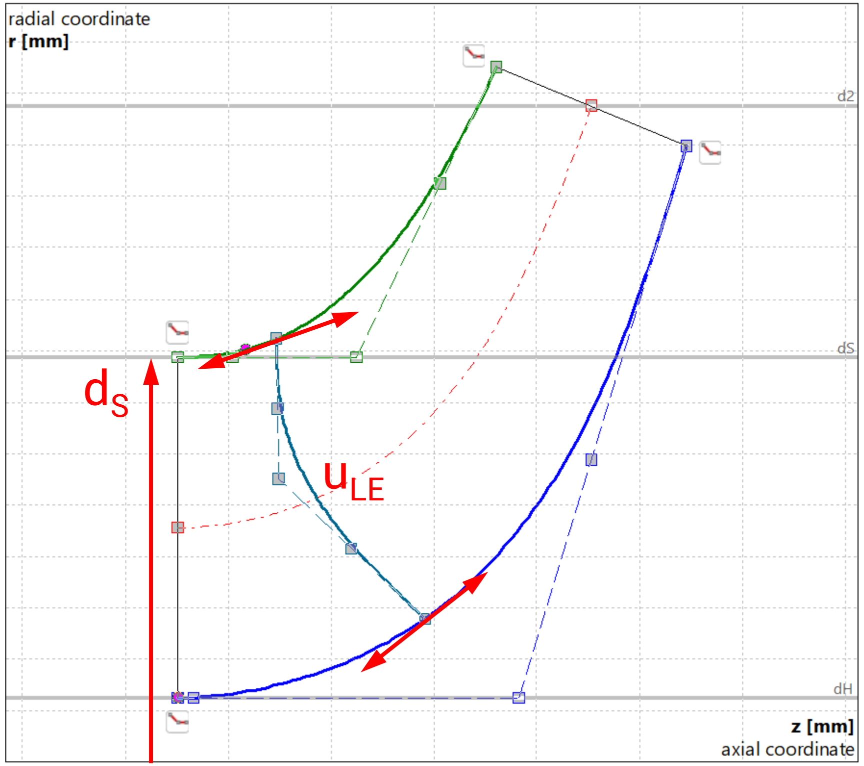


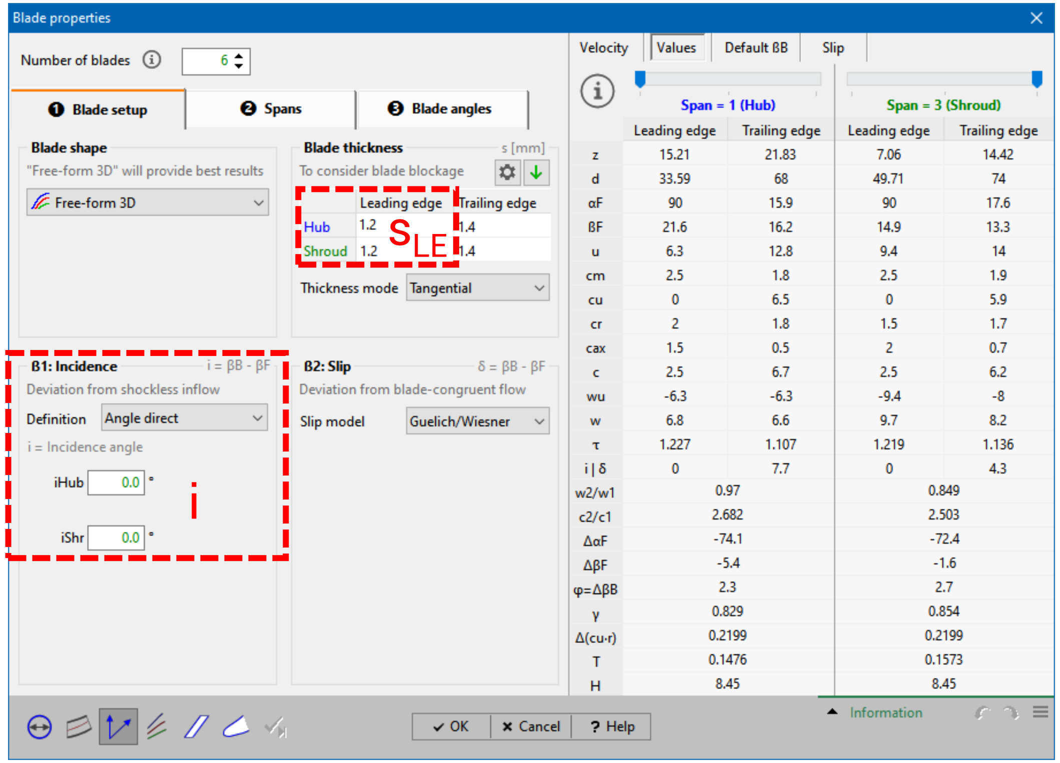
4 Project examples

❷ Multistage pump optimization

b) $NPSH_R$ optimization of first impeller – Geometry parameters

Fixed	Outlet dimensions d_2, b_2	Blade angles at leading edge are calculated automatically
	Axial extent	Blade angles at trailing edge
	Meridional shape	Number of blades
Flexible	Suction diameter d_S	Blade incidence at hub, shroud i
	Leading edge position at hub, shroud u_{LE}	Blade thickness at leading edge s_{LE} (constant value)





Number of blades: 6

Blade shape

"Free-form 3D" will provide best results

Free-form 3D

Blade thickness s [mm]

To consider blade blockage

	Leading edge	Trailing edge
Hub	1.2	1.4
Shroud	1.2	1.4

Thickness mode: Tangential

ß1: Incidence i = ßB - ßF

Deviation from shockless inflow

Definition: Angle direct

i = Incidence angle

iHub: 0.0 °

iShr: 0.0 °

ß2: Slip δ = ßB - ßF

Deviation from blade-congruent flow

Slip model: Guelich/Wiesner

	Span = 1 (Hub)		Span = 3 (Shroud)	
	Leading edge	Trailing edge	Leading edge	Trailing edge
z	15.21	21.83	7.06	14.42
d	33.59	68	49.71	74
αF	90	15.9	90	17.6
ßF	21.6	16.2	14.9	13.3
u	6.3	12.8	9.4	14
cm	2.5	1.8	2.5	1.9
cu	0	6.5	0	5.9
cr	2	1.8	1.5	1.7
cax	1.5	0.5	2	0.7
c	2.5	6.7	2.5	6.2
wu	-6.3	-6.3	-9.4	-8
w	6.8	6.6	9.7	8.2
τ	1.227	1.107	1.219	1.136
i | δ	0	7.7	0	4.3
w2/w1	0.97		0.849	
c2/c1	2.682		2.503	
ΔαF	-74.1		-72.4	
ΔßF	-5.4		-1.6	
φ=ΔßB	2.3		2.7	
γ	0.829		0.854	
Δ(cu·r)	0.2199		0.2199	
T	0.1476		0.1573	
H	8.45		8.45	

4 Project examples ❷ Multistage pump optimization

b) NPSH$_R$ optimization of first impeller – Strategy

Steady-state simulations with **Simerics** using cavitation modeling

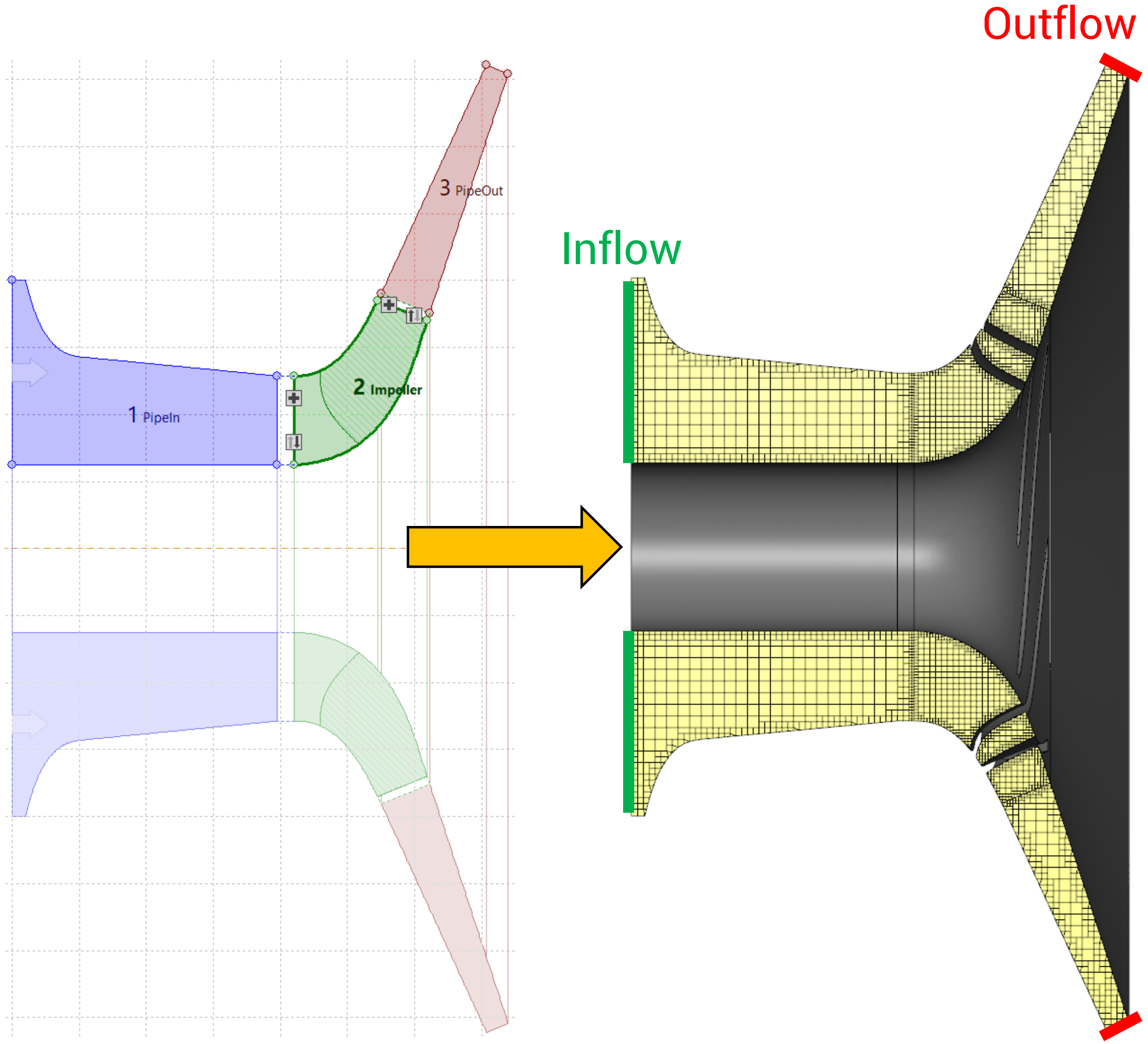
For one design iteration:

(1) Cavitation-free operating: high total pressure at inlet

(2) Operating with cavitation: lower total pressure at inlet

2 objectives:

- ⇨ Calculate relative performance reduction between (1) and (2) due to cavitation effects
- ⇨ Evaluate efficiency for cavitation-free operating conditions



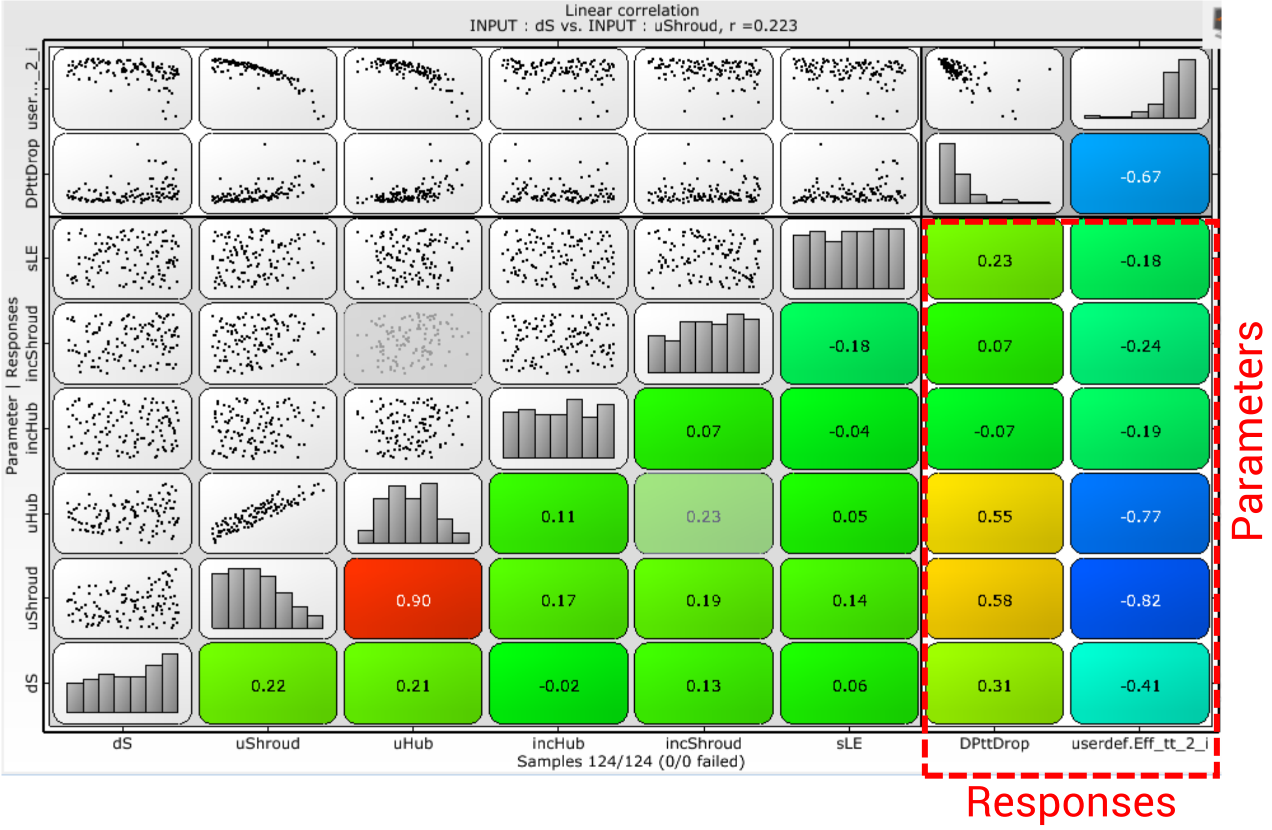
b) NPSH$_R$ optimization of first impeller – Sensitivity Analysis with DAKOTA

- 6 geometry parameters
- 2 relevant responses from CFD analysis:
  - (1) Relative performance reduction due to cavitation
  - (2) Impeller efficiency under cavitation-free operating conditions
- Sensitivity by DACE method (Design and Analysis of Computer Experiments) using Latin Hypercube Sampling = initial population for the multi-objective genetic algorithm

DACE statistics:

- 200 designs created (**steady-state simulations**)
- 1 design creation failed
- 75 design were removed from the final data set (did not meet the specified convergence criteria)

Correlation matrix with ant hill plots



Linear correlation
INPUT : dS vs. INPUT : uShroud, r =0.223

Parameter | Responses	dS	uShroud	uHub	incHub	incShroud	sLE	DPttDrop	userdef.Eff_tt_2_i
user..._2_i								
DPttDrop								-0.67
sLE							0.23	-0.18
incShroud						-0.18	0.07	-0.24
incHub					0.07	-0.04	-0.07	-0.19
uHub				0.11	0.23	0.05	0.55	-0.77
uShroud			0.90	0.17	0.19	0.14	0.58	-0.82
dS		0.22	0.21	-0.02	0.13	0.06	0.31	-0.41

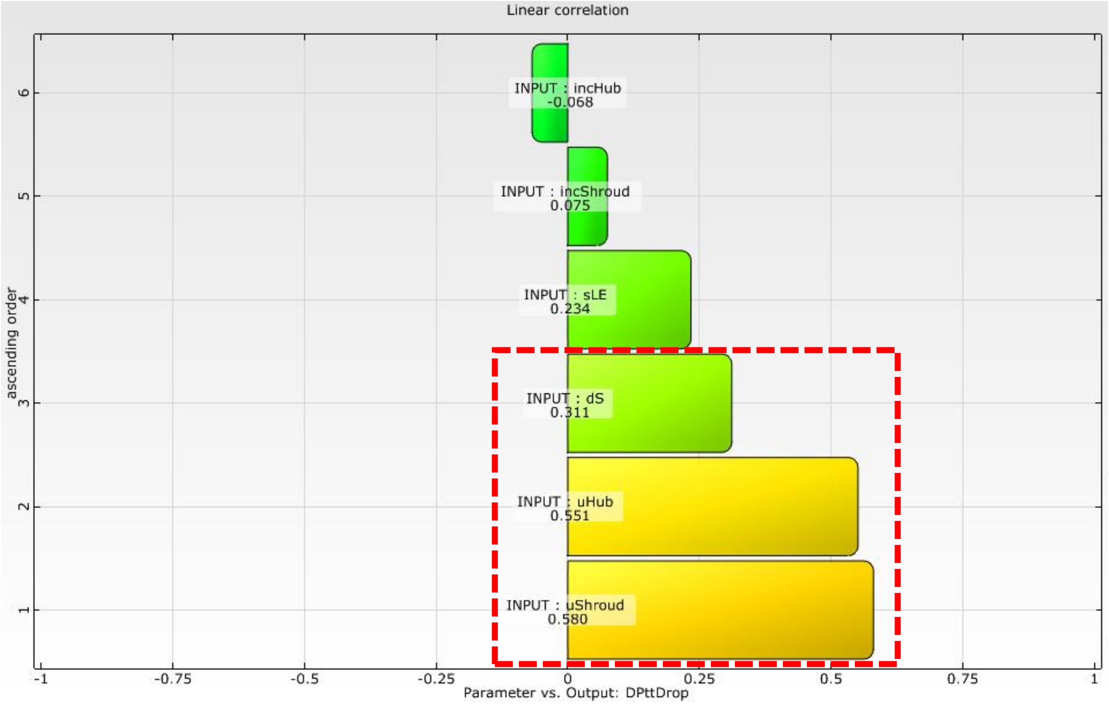
Samples 124/124 (0/0 failed)

4 Project examples ❷ Multistage pump optimization

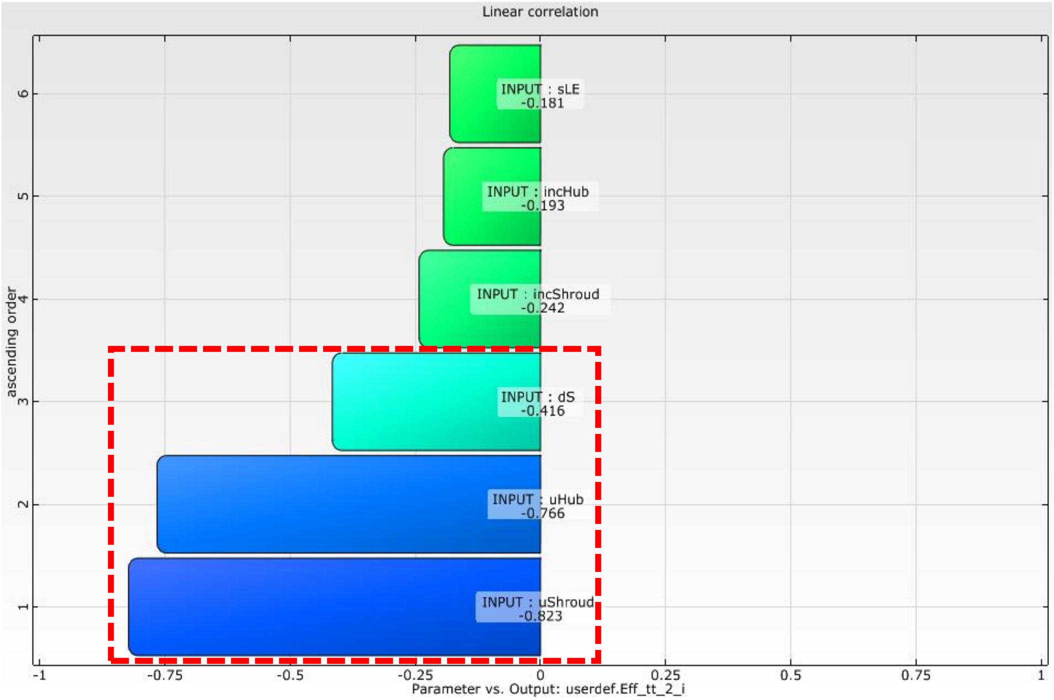
b) NPSH$_R$ optimization of first impeller – Sensitivity Analysis with DAKOTA

- Leading edge position closer to impeller inlet (= smaller u$_{Hub}$, u$_{Shroud}$)
  → smaller performance reduction due to cavitation
  → higher efficiency
- Increased suction diameter d$_S$
  → smaller performance reduction due to cavitation
  → lower efficiency

Linear correlation: geometry parameters vs. relative **performance reduction**

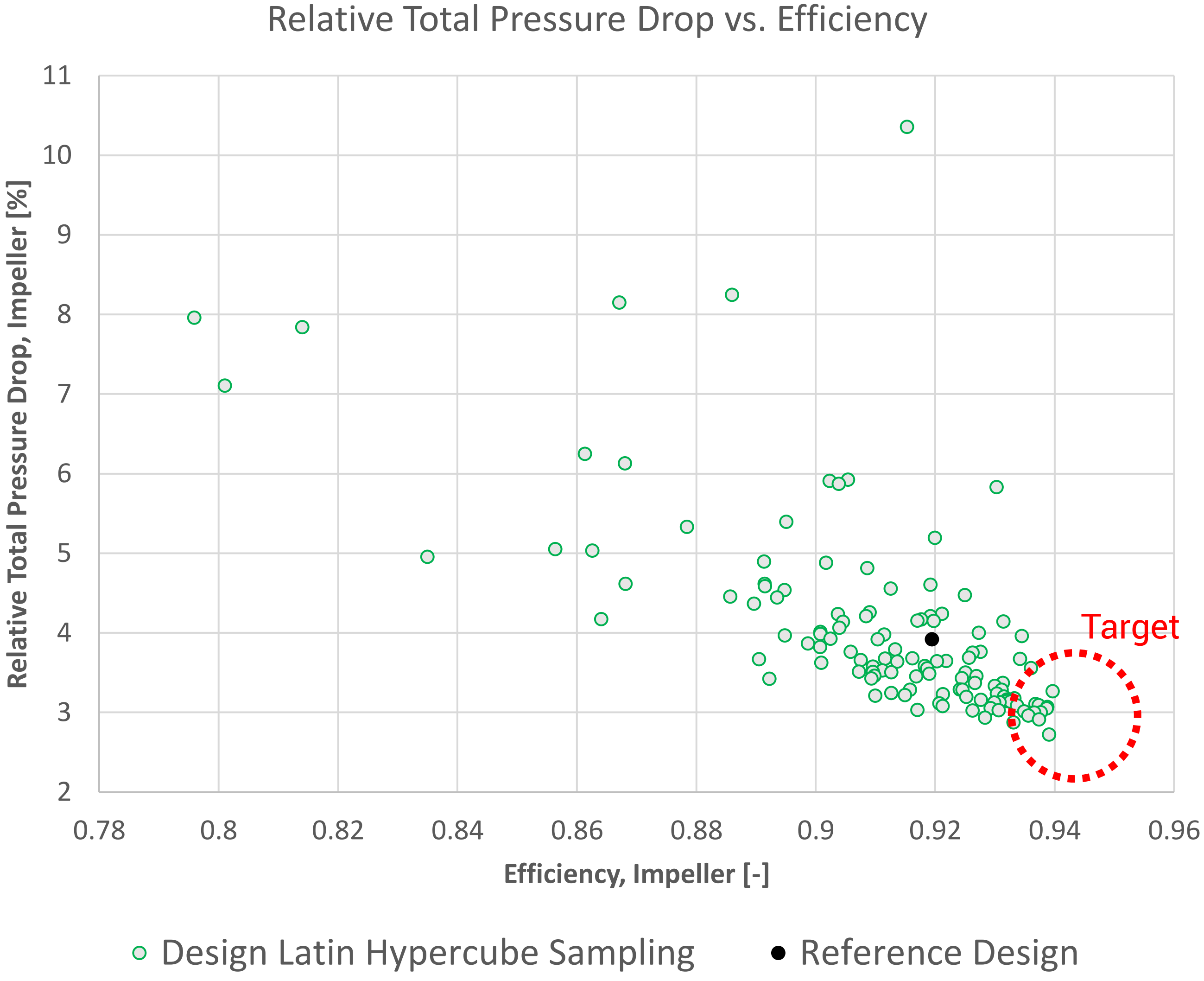


Linear correlation: geometry parameters vs. **impeller efficiency**



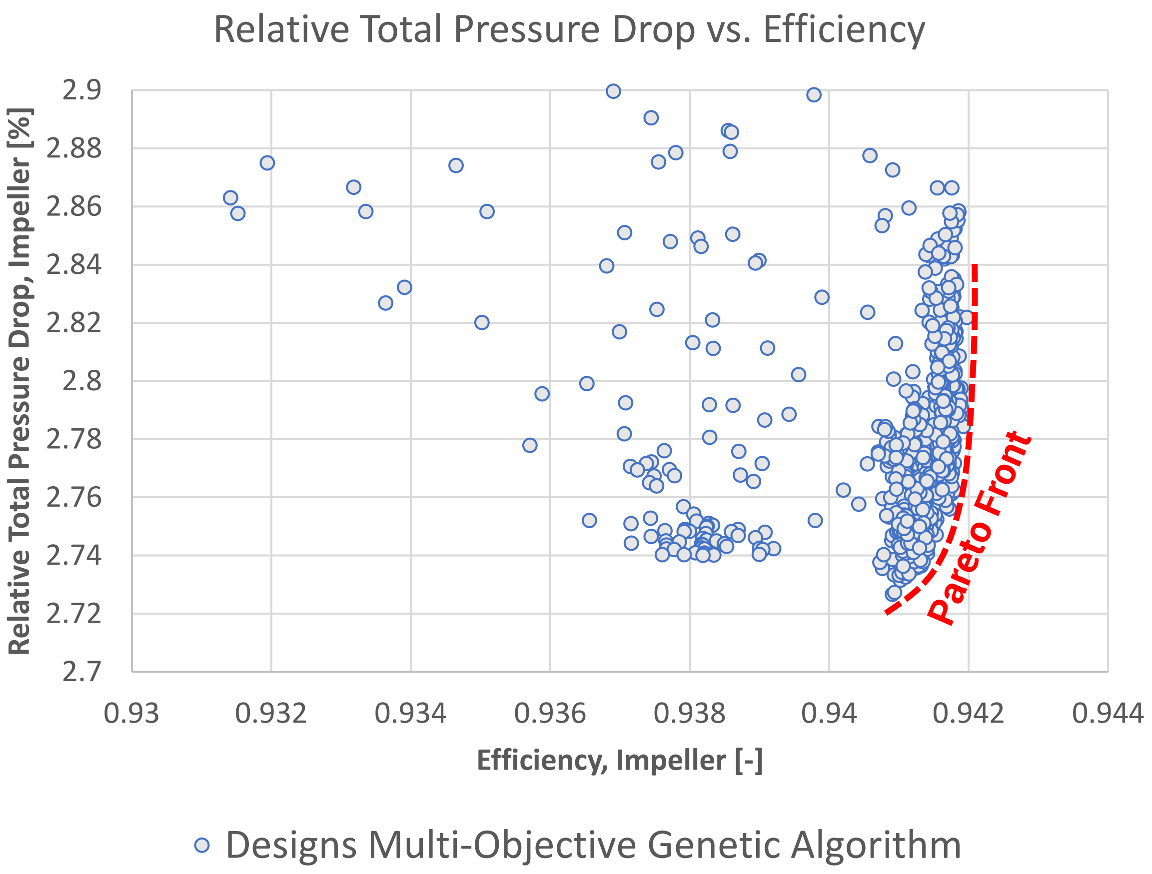
b) $NPSH_R$ optimization of first impeller – Sensitivity Analysis with DAKOTA

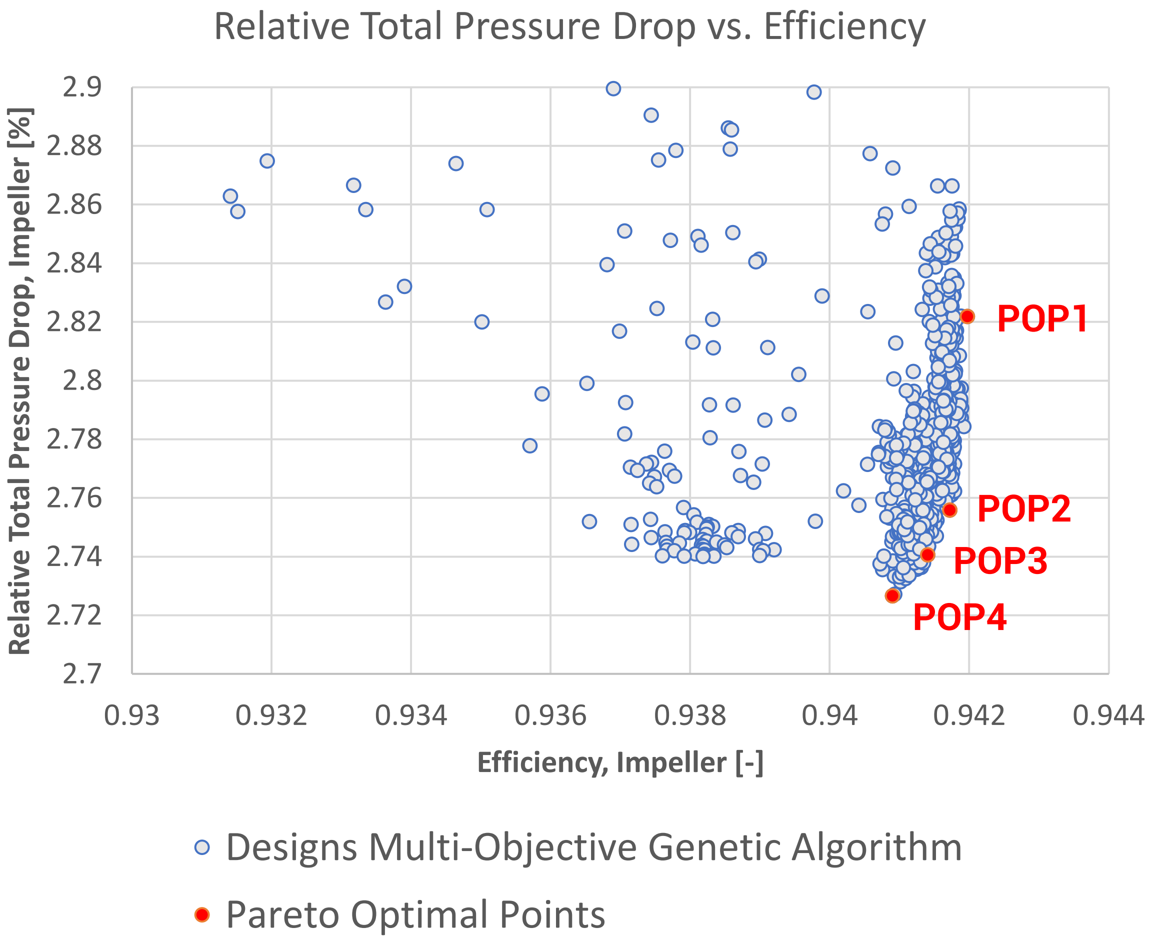
- Target marks the desired area:
  low performance reduction but high impeller efficiency
- Evaluation of 200 designs (**steady-state**) took **22 hours** with an AMD Ryzen Threadripper Pro Workstation
- 30 most promising designs from sensitivity are used as an initial population for the multi-objective genetic algorithm (MOGA)



b) $\mathrm{NPSH_R}$ optimization of first impeller – Optimization with DAKOTA

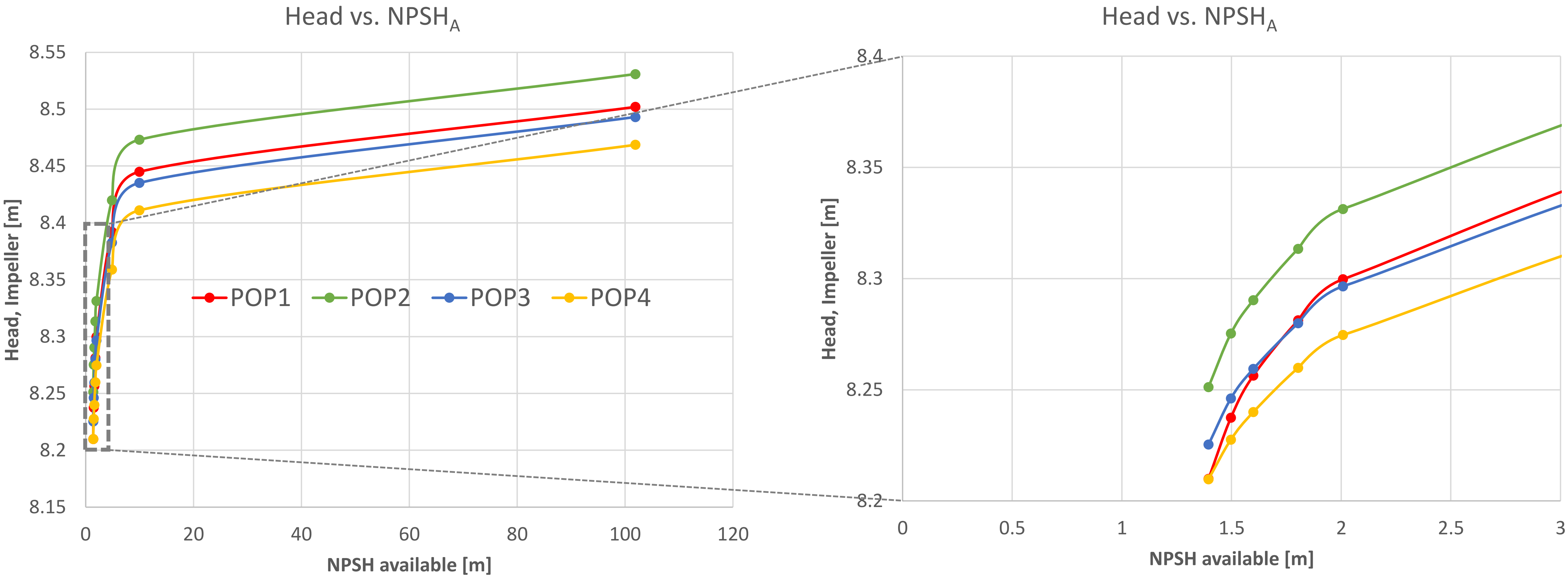
- MOGA had the objective to maximize impeller efficiency and minimize the cavitation-induced performance drop
- Evaluation of 800 Designs took **75 hours** with an AMD Ryzen Threadripper Pro Workstation





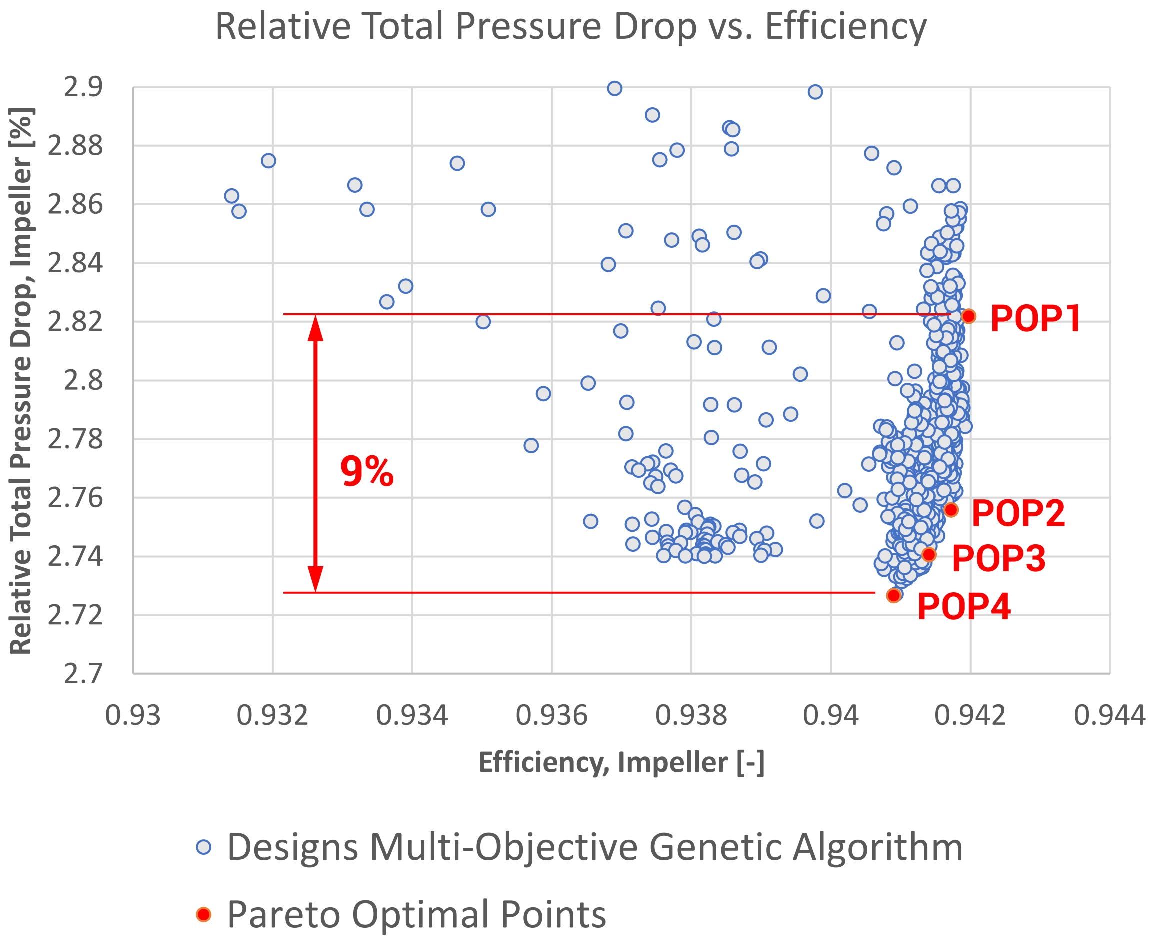
b) NPSH$_R$ optimization of first impeller – Drop curves Pareto Optimal Points (POP)

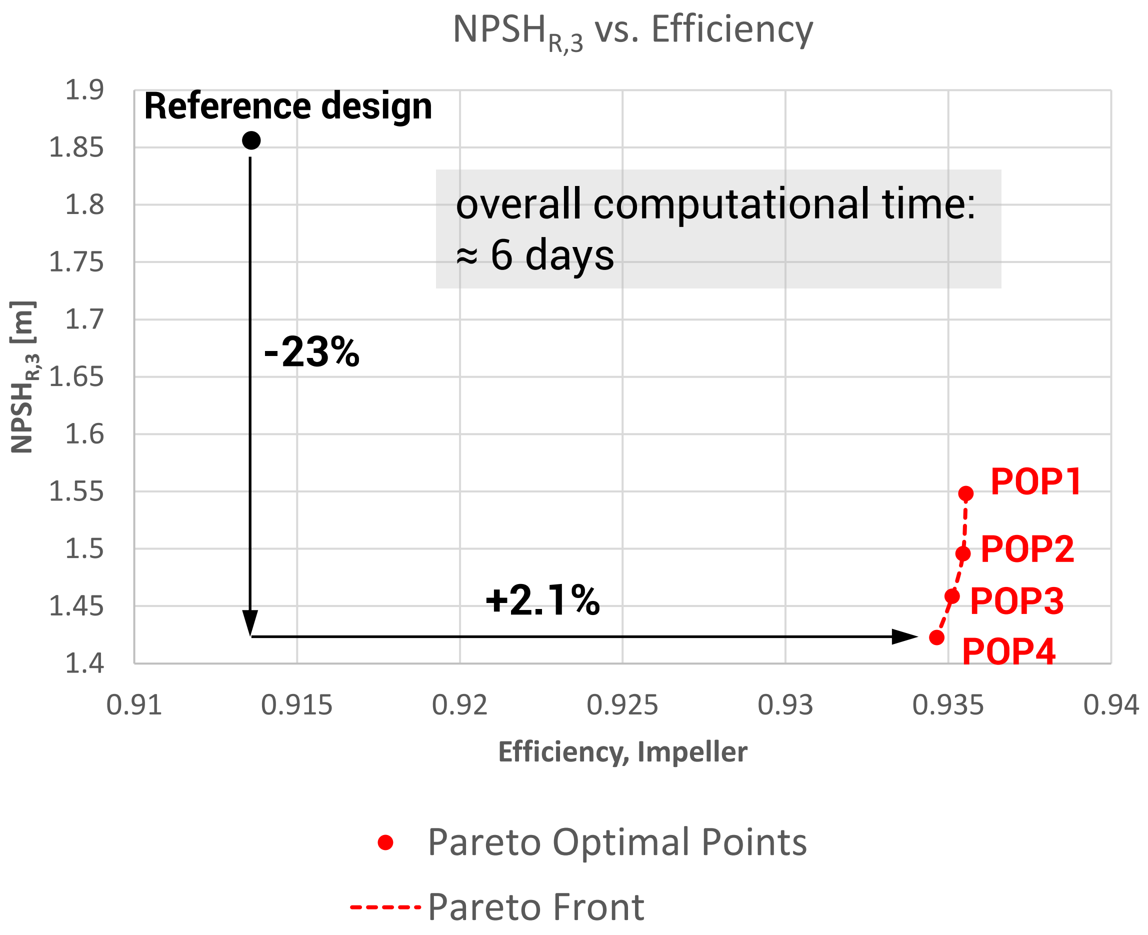
- Drop curves were calculated for the selected Pareto Optimal Points (POP) using **transient CFD analyses** (in total **40 hours** with an AMD Ryzen Threadripper Pro Workstation)
- Typical sharp drop off in the impeller performance is visible → cavitating areas increase and start to block blade passage



b) NPSH$_R$ optimization of first impeller – Drop curves Pareto Optimal Points (POP)

- NPSH$_{R,3}$ was evaluated from the **transient** drop curves for each Pareto Optimal Point (POP)
- Trend from the **steady-state** results provide a good estimation for the NPSH$_{R,3}$ evaluation from **transient** analyses



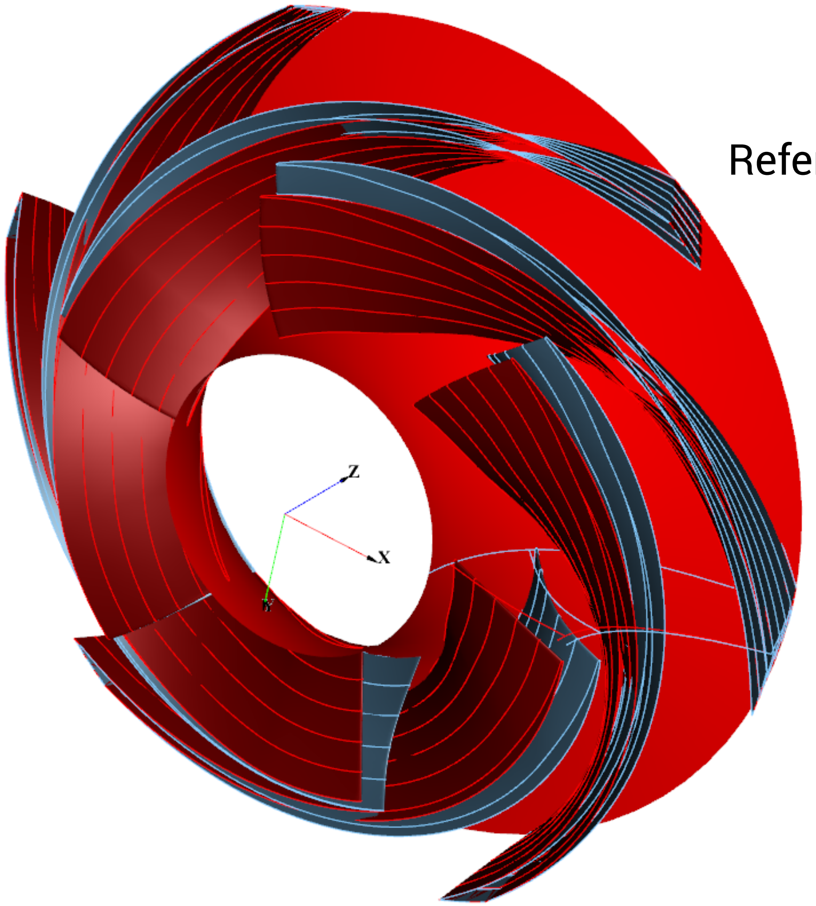


overall computational time:
≈ 6 days

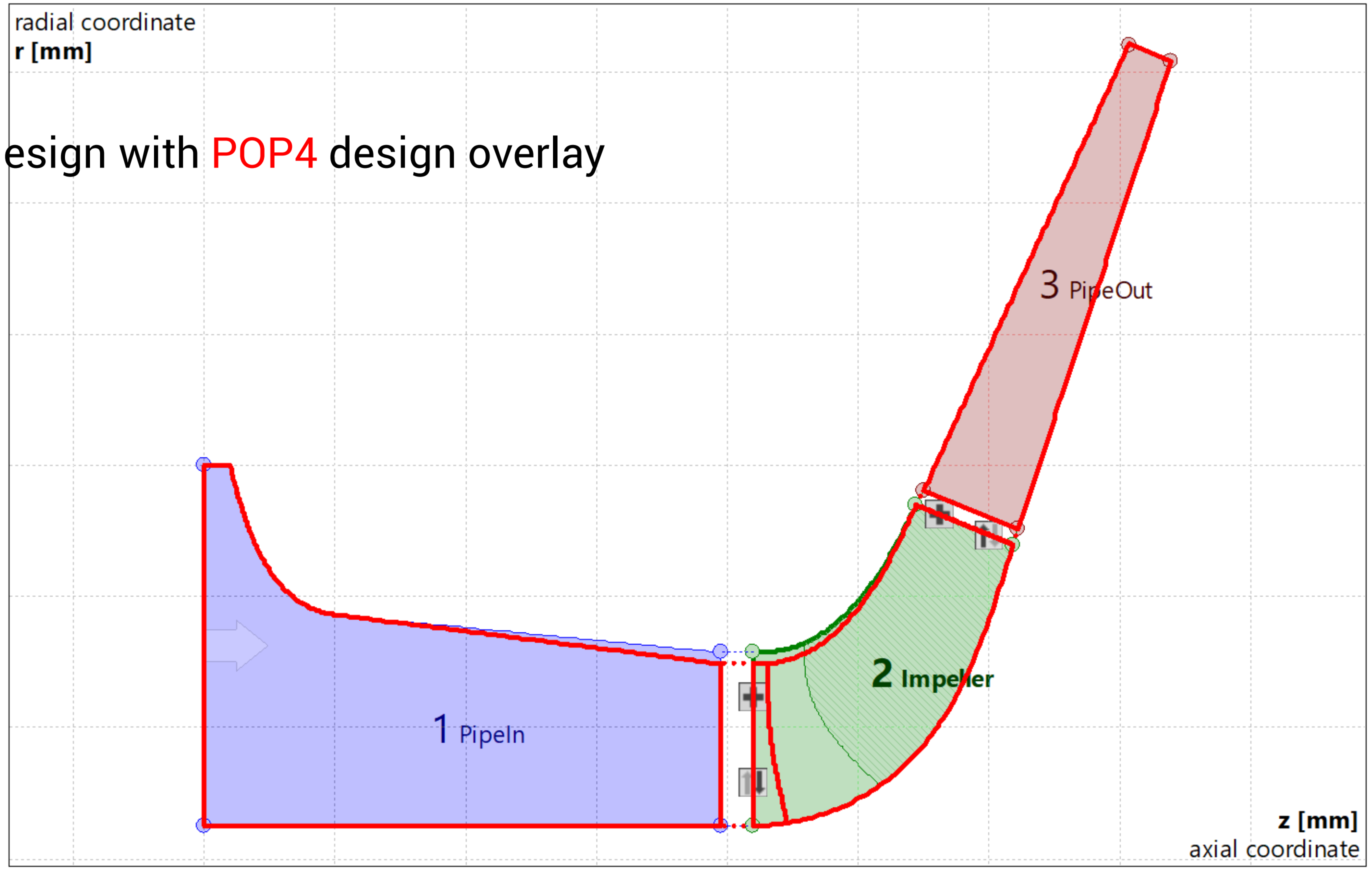
4 Project examples ❷ Multistage pump optimization

b) $NPSH_R$ optimization of first impeller – Design comparison

Design iteration POP4:
- smaller suction diameter d_S
- leading edge was moved closer to the impeller inlet



Reference design with POP4 design overlay

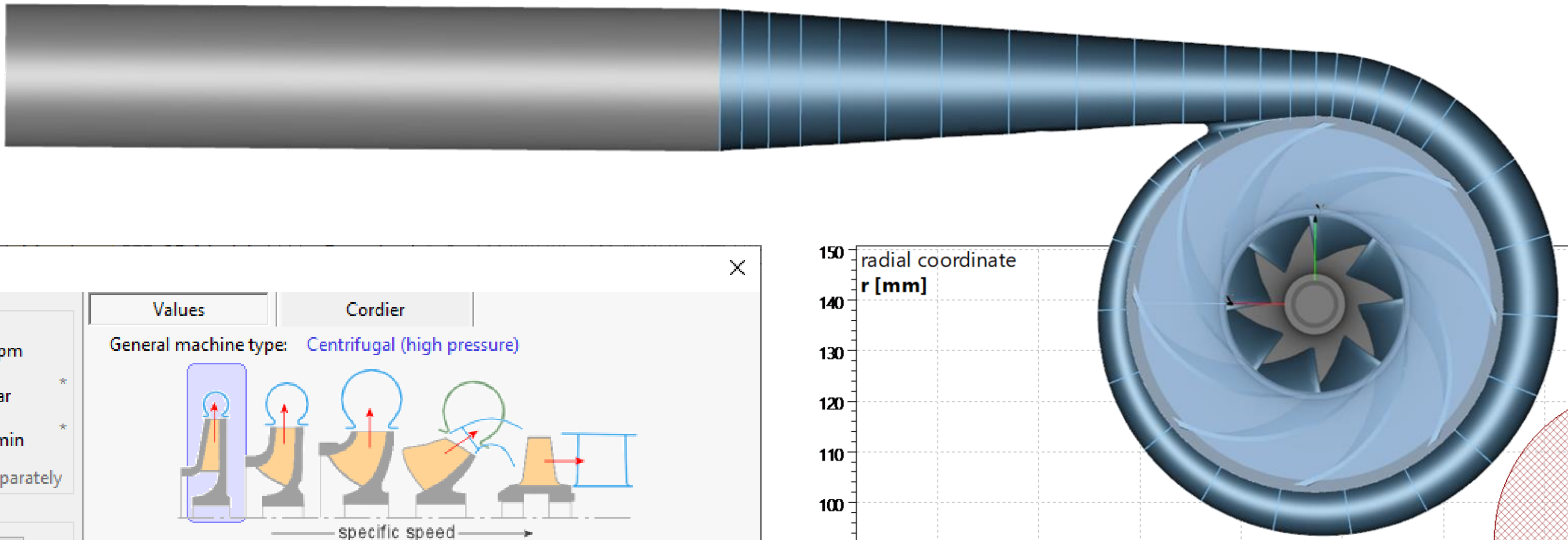


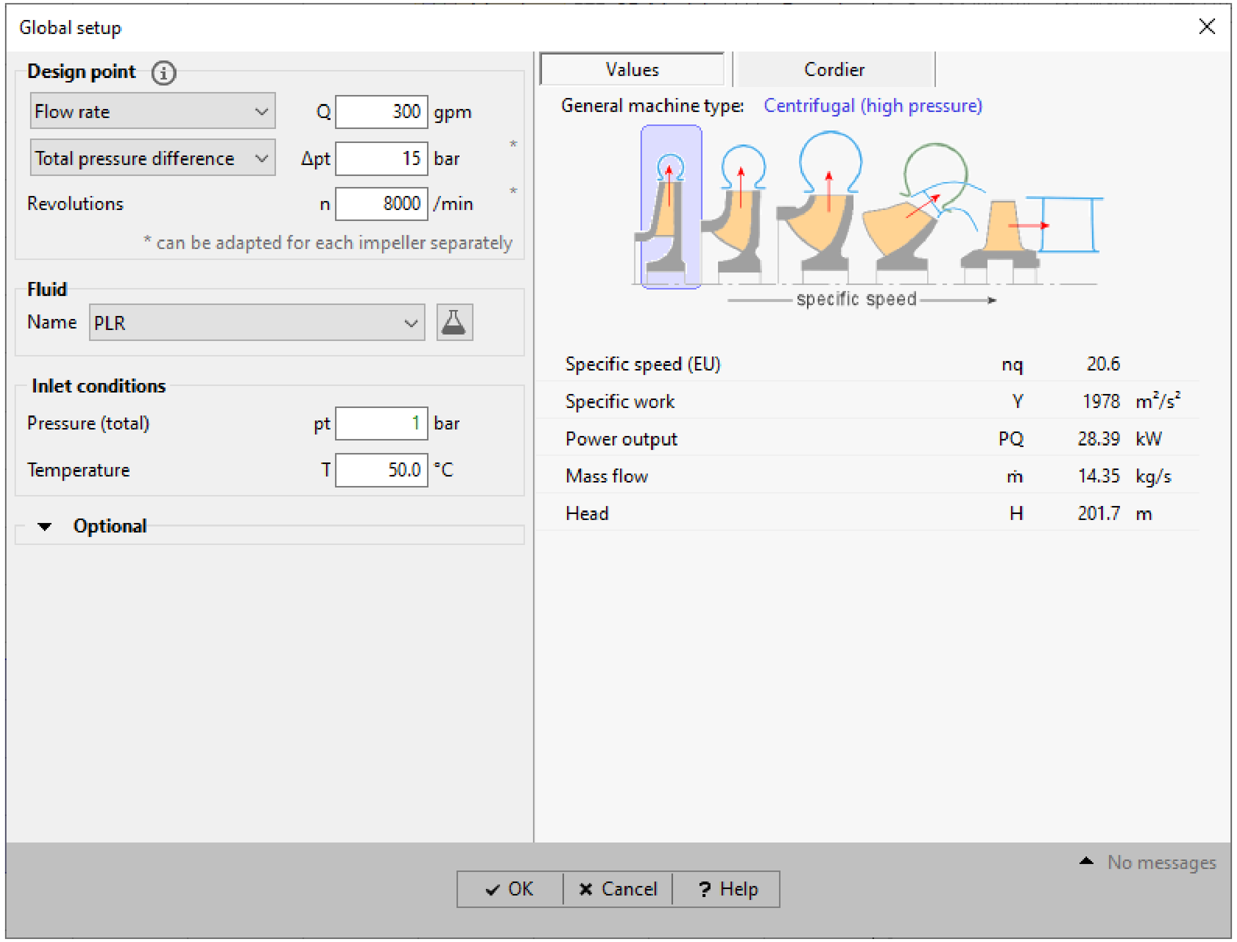
Topics

4 Optimization project examples

❸ Material contour optimization

Application:
Jet fuel pump





Global setup

Design point

Flow rate	Q	300	gpm
Total pressure difference	Δpt	15	bar *
Revolutions	n	8000	/min *

* can be adapted for each impeller separately

Fluid

Name: PLR

Inlet conditions

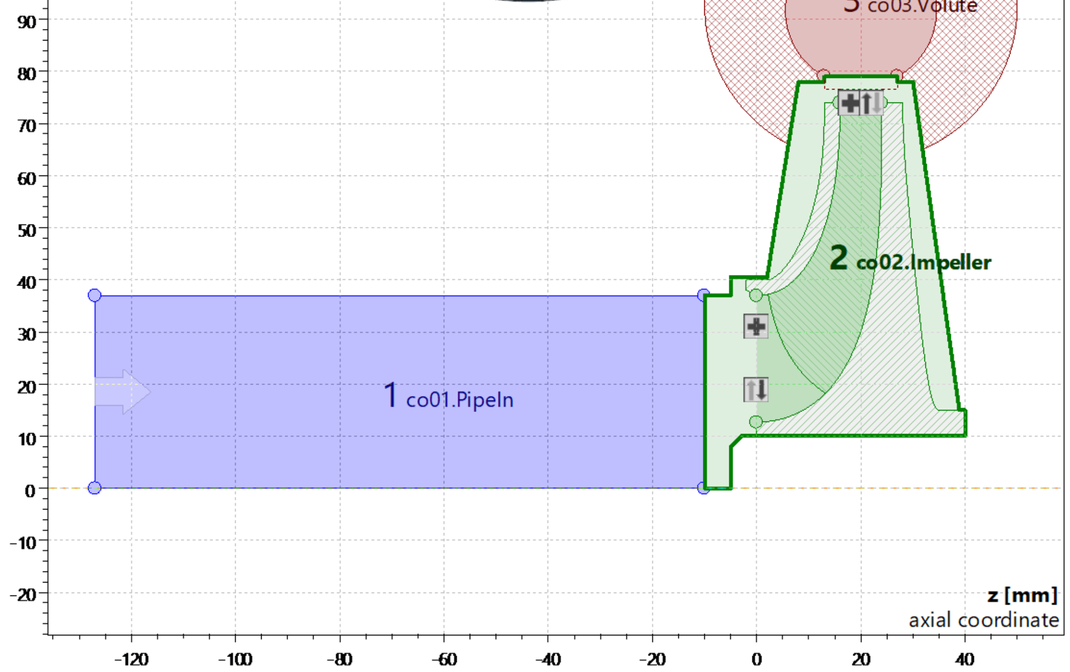
Pressure (total)	pt	1	bar
Temperature	T	50.0	°C

Optional

General machine type: Centrifugal (high pressure)

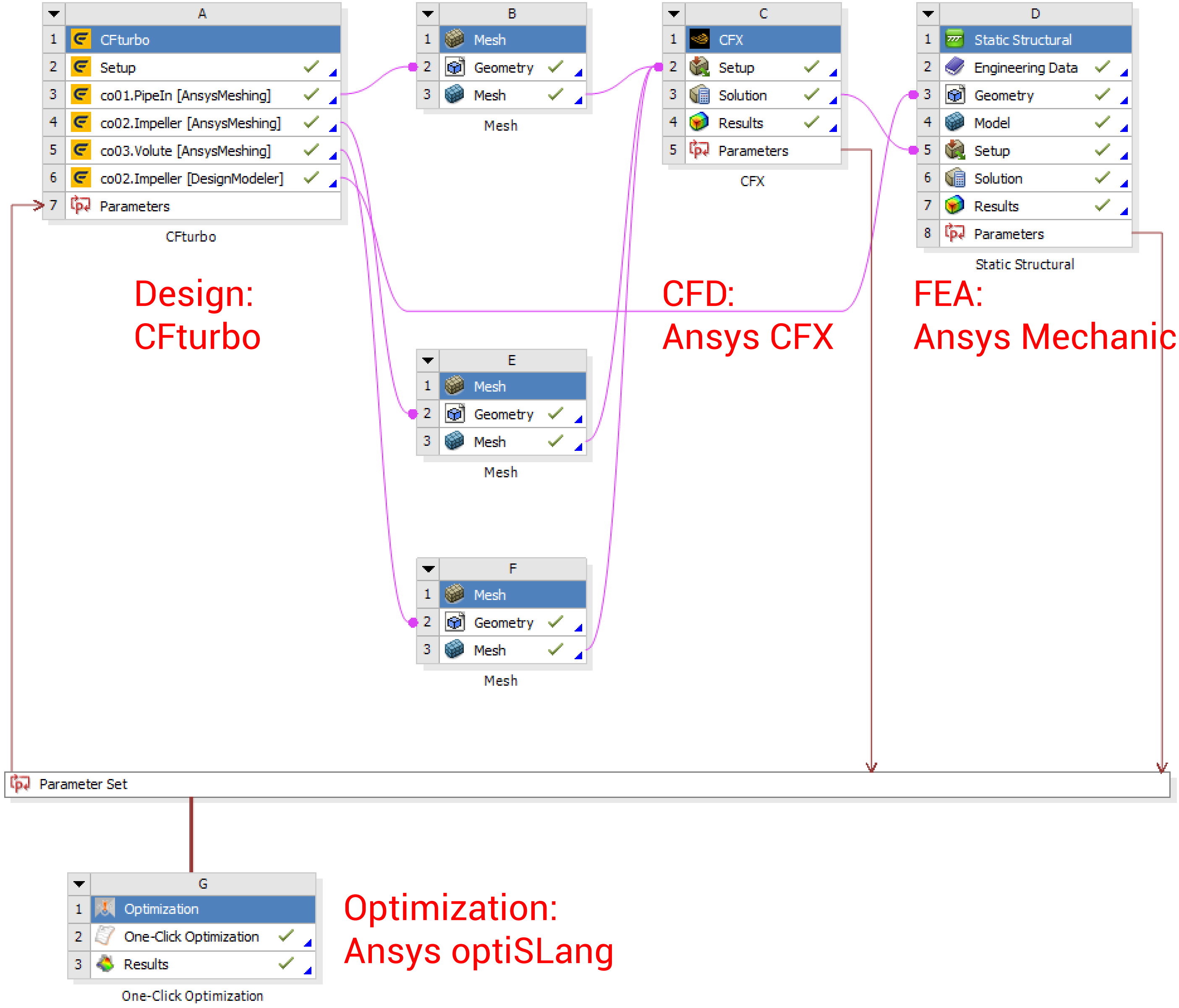
Specific speed (EU)	nq	20.6	
Specific work	Y	1978	m^2/s^2
Power output	PQ	28.39	kW
Mass flow	ṁ	14.35	kg/s
Head	H	201.7	m

No messages



4 Project examples — ❸ Material contour optimization

Workflow in
Ansys Workbench



Design:
CFturbo

CFD:
Ansys CFX

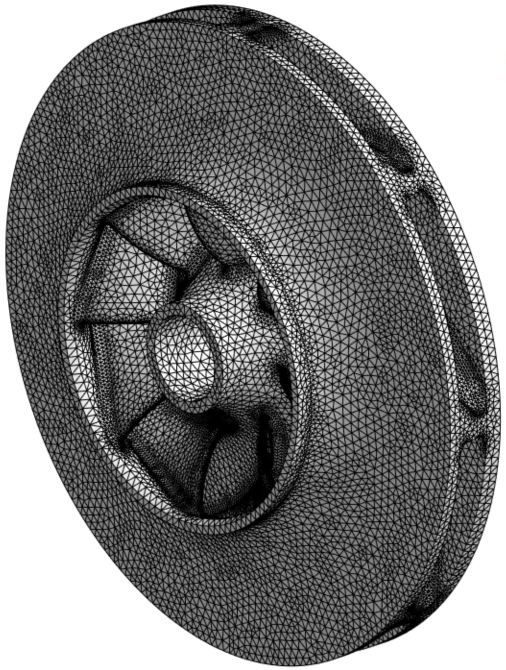
FEA:
Ansys Mechanical

Optimization:
Ansys optiSLang

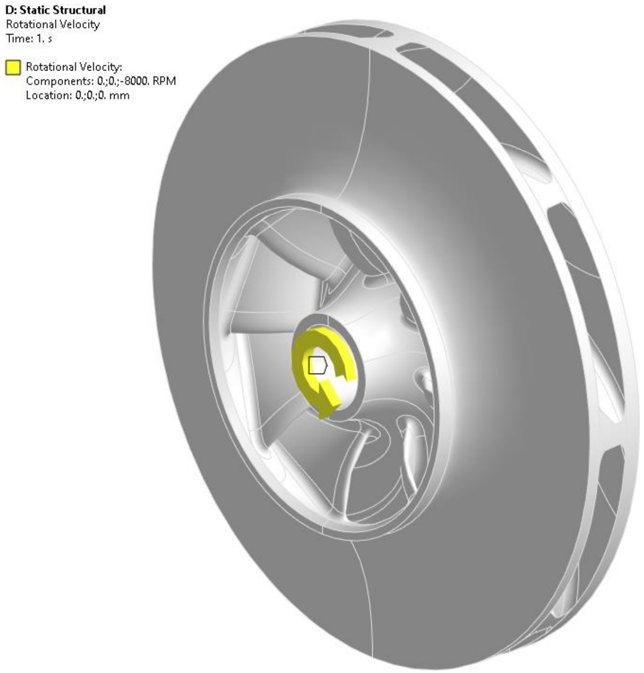
4 Project examples

❸ Material contour optimization

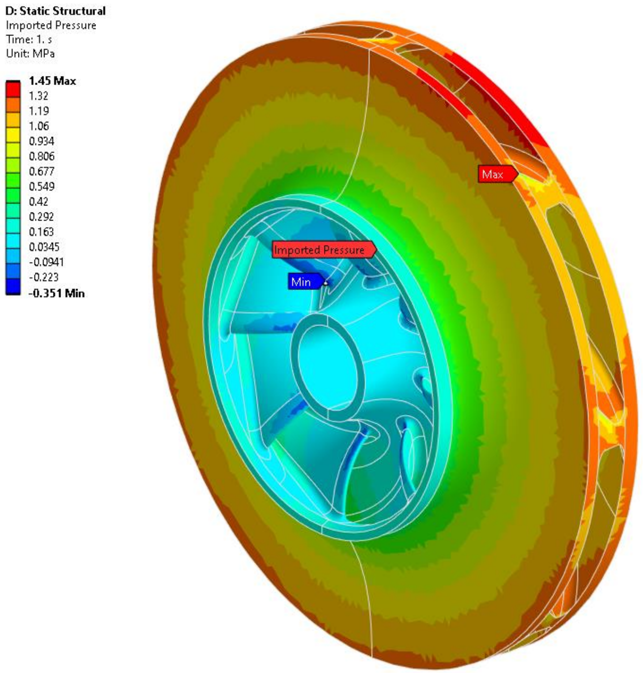
Workflow for static structural



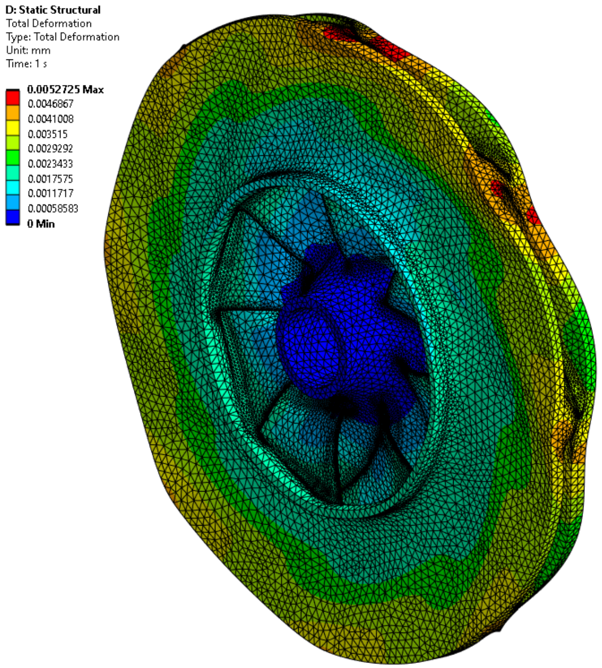
Mesh of impeller material domain



Rotational velocity is applied to impeller material domain



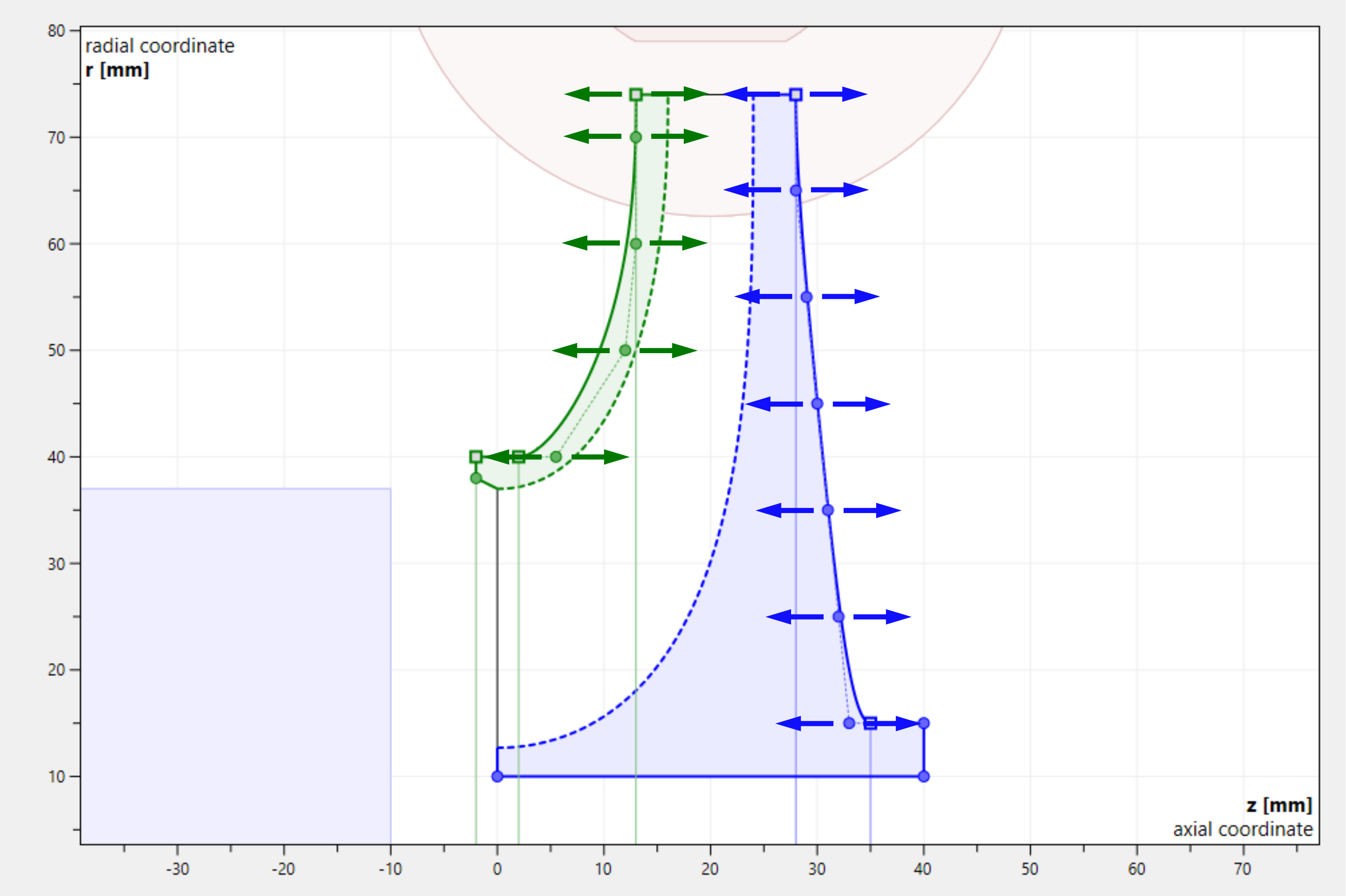
Pressure field from CFD solution mapped to impeller material domain



Deformation and equivalent stress is solved in Finite Element Analysis (FEA)

❸ Material contour optimization

Parameters



- Axial coordinates of selected material contour control points = 12 parameters
- Blade fillet radius at hub and shroud = 2 parameters
- Blade thickness (overall constant) = 1 parameter

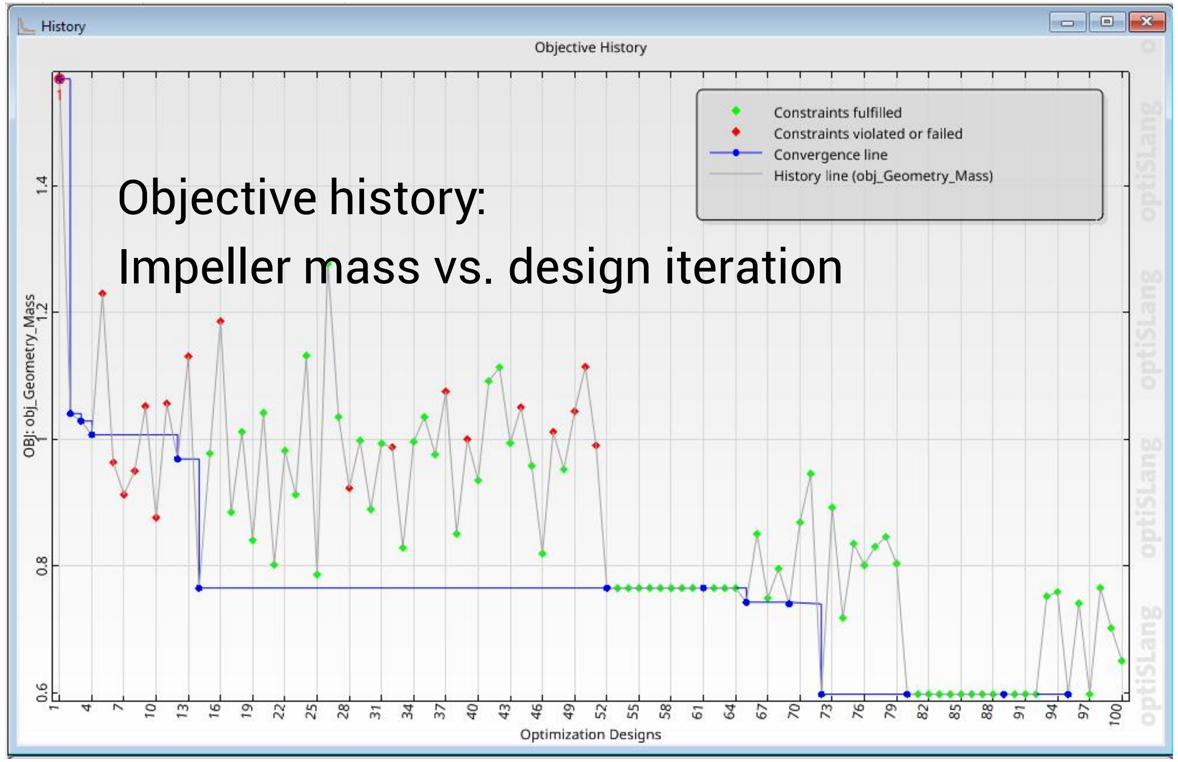
⇨ 15 parameters

4 Project examples

❸ Material contour optimization

Optimization with Ansys optiSLang

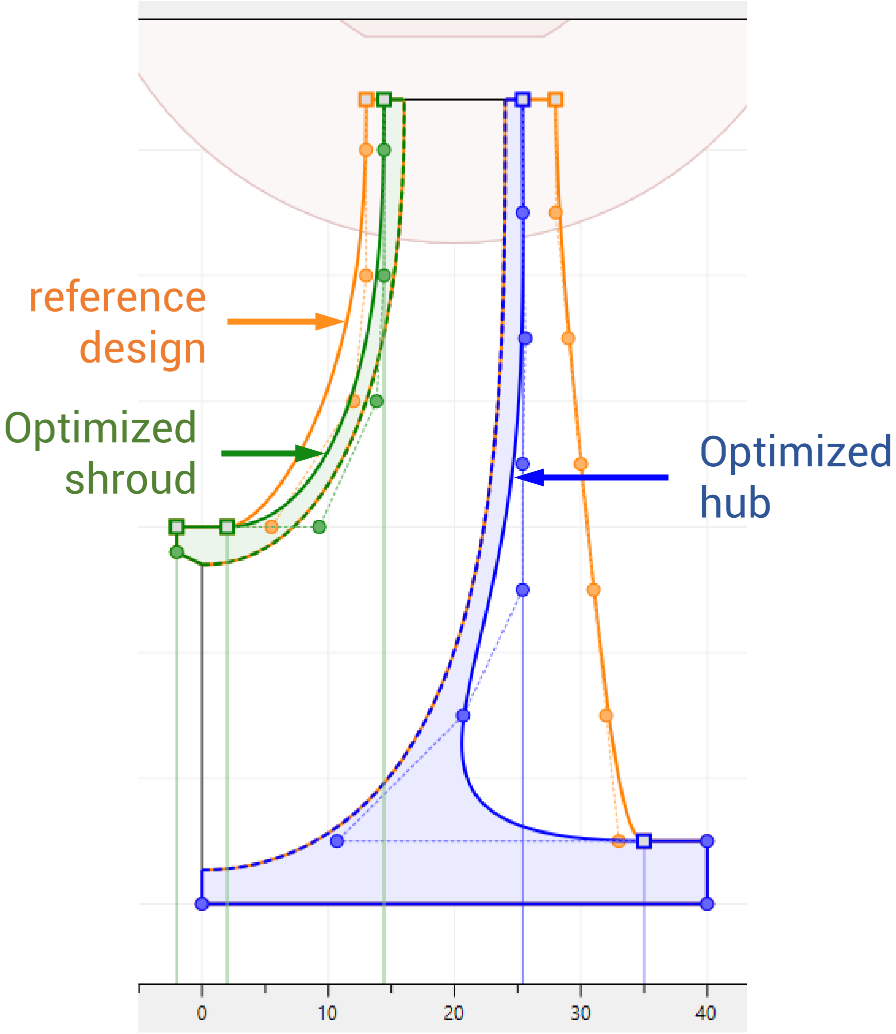
- **Objective**: Reduce mass of impeller wheel geometry
- **Constraints**: Equivalent Stress Maximum < 100 MPa
  Total Deformation Maximum < 0.1 mm
- **Method**: „One-Click-Optimization“ with 100 design evaluations



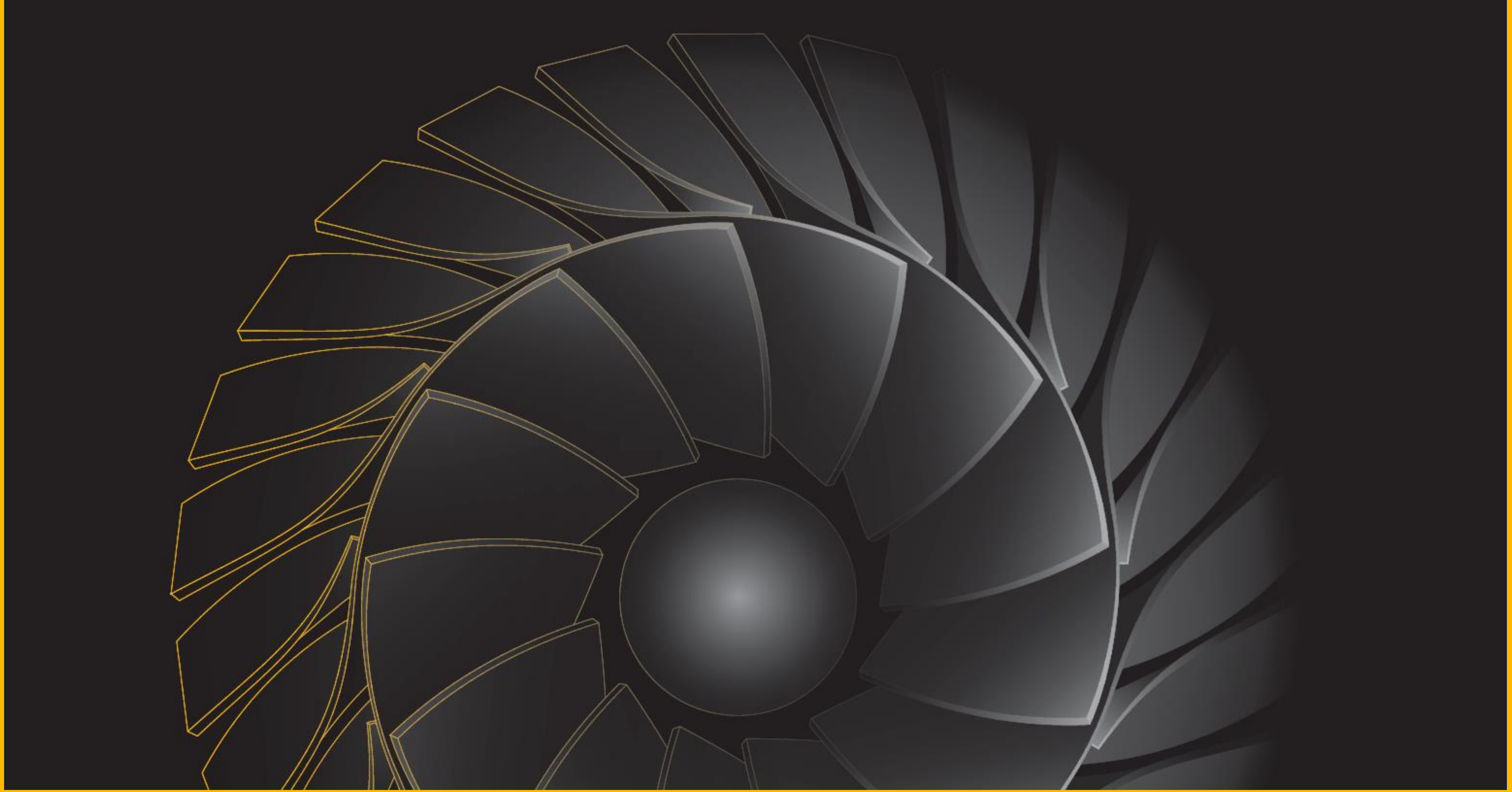
Objective history:
Impeller mass vs. design iteration

- Overall project run time (Intel Xeon W-2255): ≈ 42 hours
- Run time for single design iteration:
  - a) CFD meshing + solver run (1.9 million nodes): ≈ 25 minutes (83%)
  - b) FEA meshing + solver run (0.7 million nodes): ≈ 5 minutes (17%)

Design comparison



Responses	Reference	Optimized	Criteria	
Geometry Mass	1.569 kg	0.598 kg	minimize	(objective)
Equivalent Stress Max.	40.8 MPa	73.7 MPa	< 100 MPa	(constraint)
Total Deformation Max.	0.005 mm	0.095 mm	< 0.1 mm	(constraint)



Thank you for your attention!

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