

**WOST 2018**

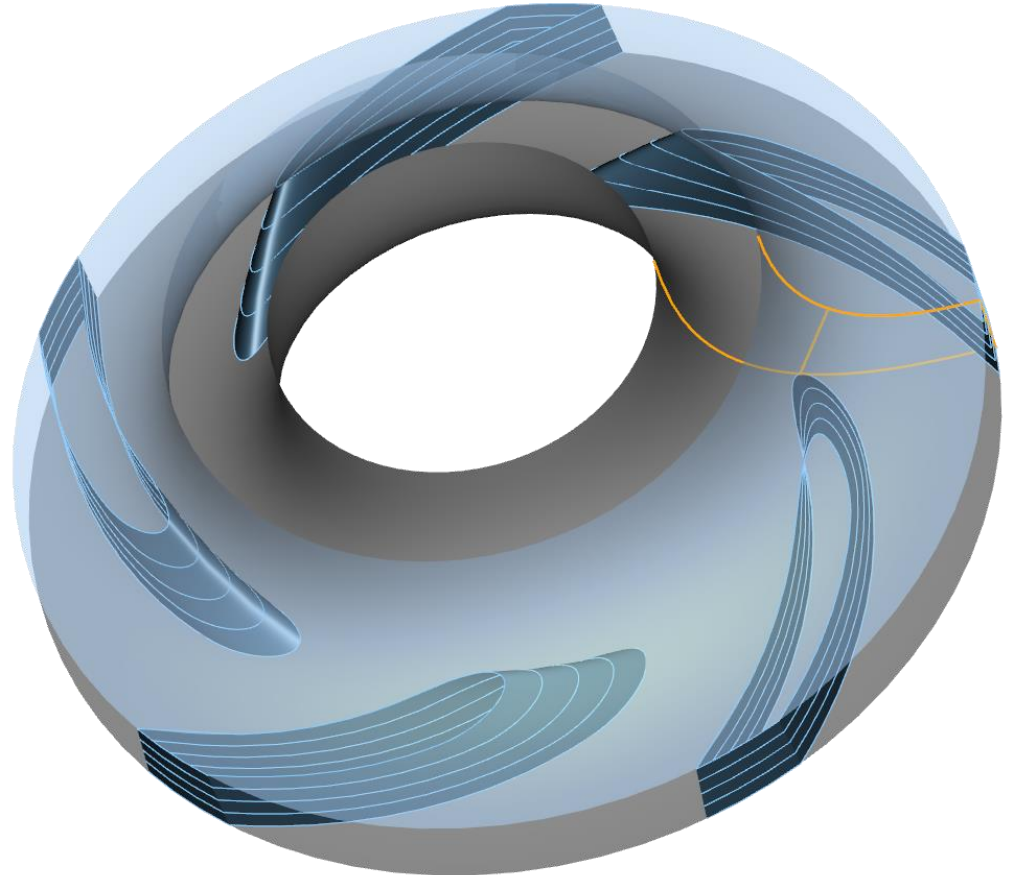
# Optimization of a Radial Pump using CFturbo, TCFD & optiSLang

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CFturbo GmbH



## Content

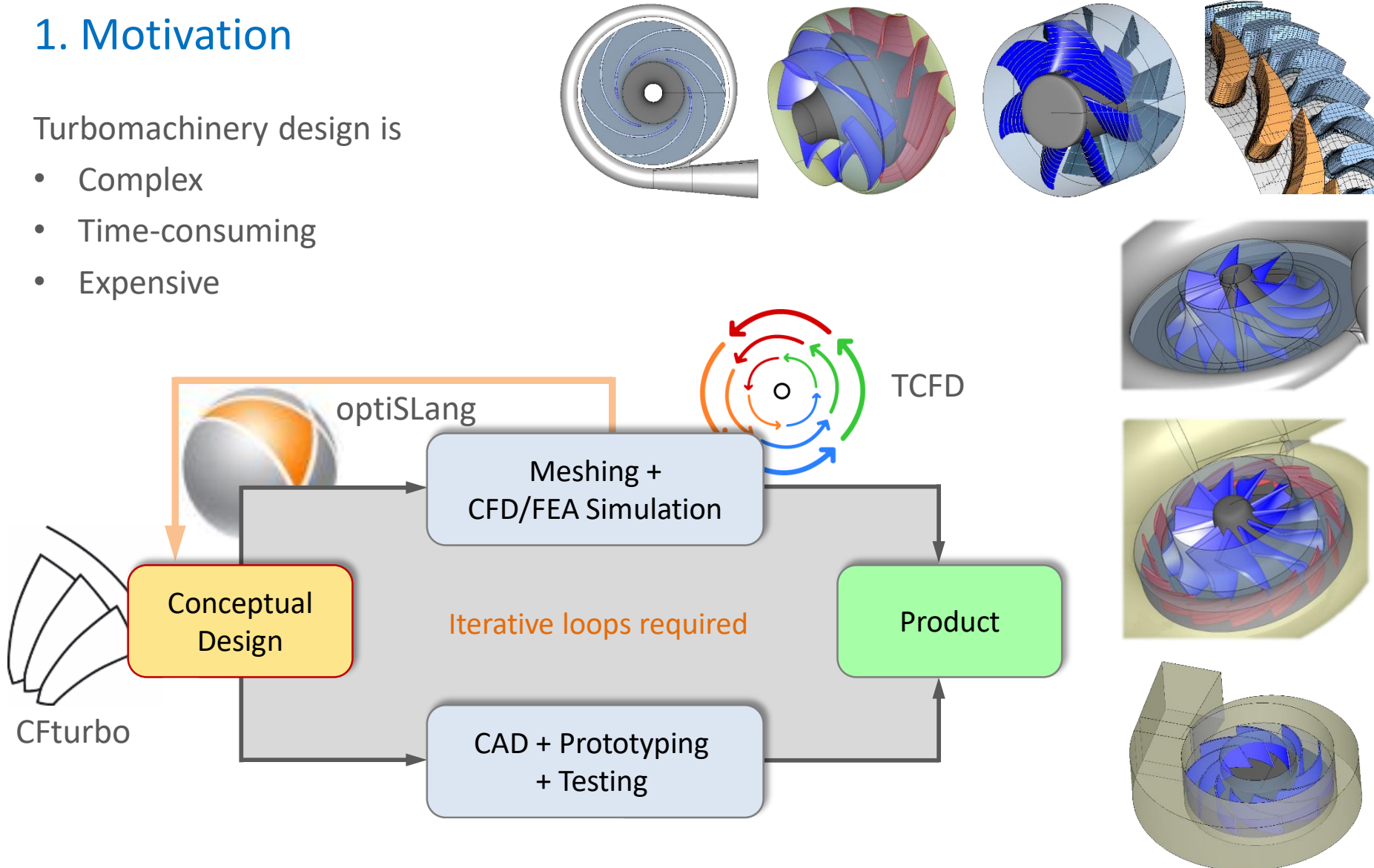
1. Motivation
2. Software tools
  - a) CFturbo
  - b) TCFD
3. Parameters
4. Optimization workflow
5. Results
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# 1. Motivation

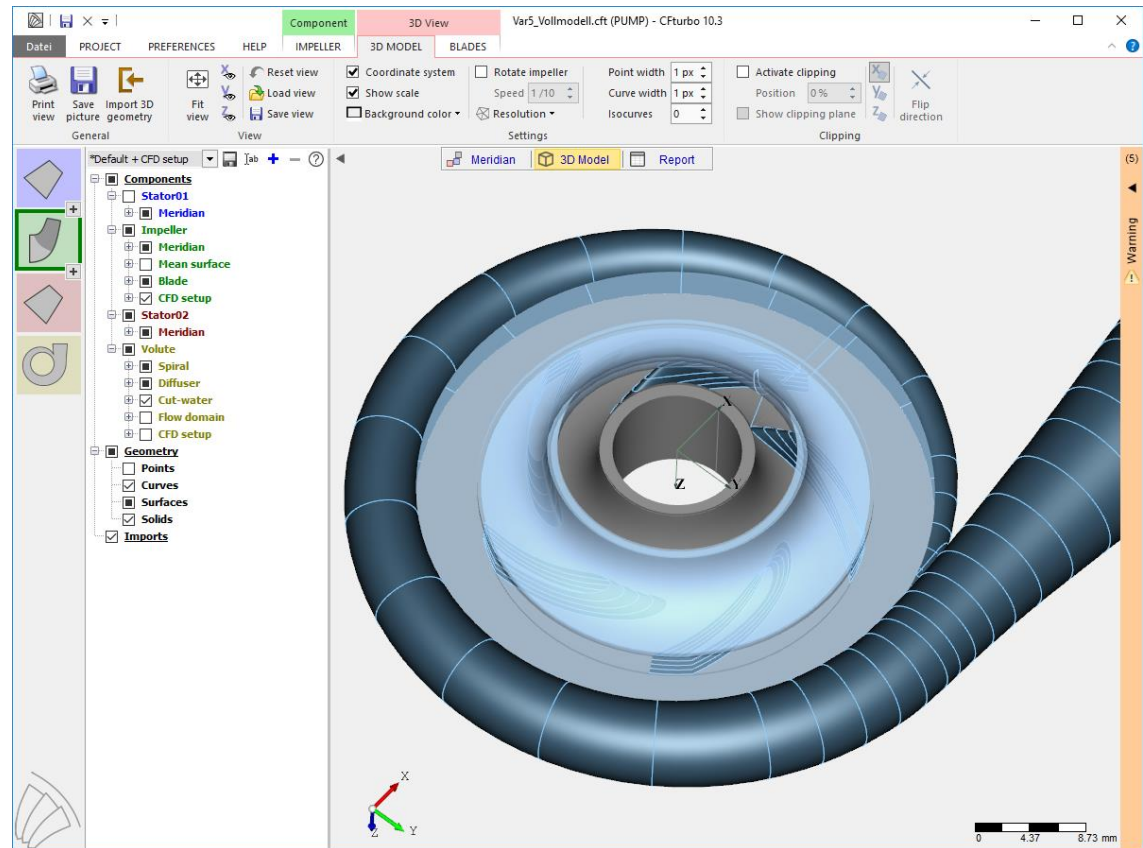
Turbomachinery design is

- Complex
- Time-consuming
- Expensive



## 2. Software tools a) CFturbo

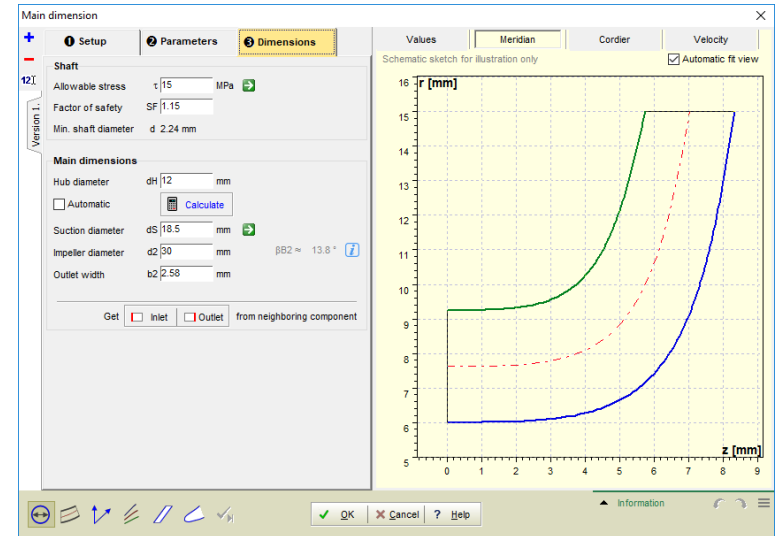
- Modern turbomachinery design software for
  - ✓ Pumps
  - ✓ Ventilators
  - ✓ Compressors
  - ✓ Turbines
- Covers all major types:
  - ✓ Radial
  - ✓ Mixed-flow
  - ✓ Axial
- Available components:
  - ✓ Impeller
  - ✓ Volute
  - ✓ Vaned/vaneless stators
- Analytical design theory & empirical correlations



→ Fully parametric geometry model of machines

## 2. Software tools a) CFturbo

- Several design steps from design point to 3D geometry
- All parameters can be accessed via batch mode per XML file
- optiSLang integration available



Batch mode/ optimization

Parameters Settings

Expand to level: 1 2 3 all Select nodes: All None

| NAME                    | DESCRIPTION                                                        | SYMBOL | UNIT     | VALUE                                                                                | CONS... |
|-------------------------|--------------------------------------------------------------------|--------|----------|--------------------------------------------------------------------------------------|---------|
| PROJECT: Var5_Impeller  |                                                                    |        |          |                                                                                      |         |
| 1: Zulauf               |                                                                    |        |          |                                                                                      |         |
| Main dimensions         |                                                                    |        |          |                                                                                      |         |
| Extent                  |                                                                    |        |          |                                                                                      |         |
| Hub extent              | Hub extent $\Delta z$ , $\Delta r$ (inlet $\rightarrow$ outlet)    |        | [mm, mm] | [25; 6]                                                                              | -       |
| Shroud extent           | Shroud extent $\Delta z$ , $\Delta r$ (inlet $\rightarrow$ outlet) |        | [mm, mm] | [25; 6]                                                                              | -       |
| Inlet                   |                                                                    |        |          |                                                                                      |         |
| Offset hub              | Offset Hub $\Delta z$ , $\Delta r$                                 |        | [mm, mm] | [0; 0]                                                                               | -       |
| Offset shroud           | Offset Shroud $\Delta z$ , $\Delta r$                              |        | [mm, mm] | [0; 0]                                                                               | -       |
| Outlet                  |                                                                    |        |          |                                                                                      |         |
| Offset hub              | Offset Hub $\Delta z$ , $\Delta r$                                 |        | [mm, mm] | [0; 0]                                                                               | -       |
| Offset shroud           | Offset Shroud $\Delta z$ , $\Delta r$                              |        | [mm, mm] | [0; 0]                                                                               | -       |
| Meridional contour      |                                                                    |        |          |                                                                                      |         |
| Hub Contour Controls    | Contains all editable control points of this contour.              |        | [mm, mm] | [0; 25; 0; [-21.1; 0; [-17.2; 0; [-11.35; 0; [-5.5; 0; [-5.5; 2; [-1.8333; 6; [0; 6] | -       |
| Shroud Contour Controls | Contains all editable control points of this contour.              |        | [mm, mm] | [0; 25; 9.25; [0; 9.25]                                                              | -       |
| 2: Impeller             |                                                                    |        |          |                                                                                      |         |
| Main dimensions         |                                                                    |        |          |                                                                                      |         |
| Version 1               |                                                                    |        |          |                                                                                      |         |
| Dimensions              |                                                                    |        |          |                                                                                      |         |
| Hub diameter            | Inner diameter at inlet side                                       | dH     | [mm]     | 12                                                                                   | -       |
| Suction diameter        | Outer diameter at inlet side                                       | dS     | [mm]     | 18.5                                                                                 | -       |
| Outlet width            | Distance between hub and shroud at outlet                          | b2     | [mm]     | 2.58                                                                                 | -       |
| Impeller diameter       | Defined at midline position                                        | d2     | [mm]     | 30                                                                                   | -       |
| Meridional contour      |                                                                    |        |          |                                                                                      |         |

Save to file ... Modified

Close ? Help



Var5\_Impeller.cft-batch

```

1  <?xml version="1.0" standalone="yes"?>
2  <CFturboFile Version="10.3">
3    <CFturboBatchProject InputFile=".\\Var5_Impeller.gft">
4      <Updates>
5        <CFturboProject Type="Object" Version="10.3">
6          <CFturboDesign_RadialImpeller Type="Object" Name="Impeller" Info="CFturbo GmbH -
7            <MainDimensions Type="Object">
8              <MainDimensionsElement Type="Object" Name="Version 1.">
9                <dN Type="Float" Caption="Hub diameter" Desc="Inner diameter at inlet"
10                  <dS Type="Float" Caption="Suction diameter" Desc="Outer diameter at
11                  <b2 Type="Float" Caption="Outlet width" Desc="Distance between hub and
12                  <d2 Type="Float" Caption="Impeller diameter" Desc="Defined at midline
13              </MainDimensionsElement>
14            </MainDimensions>
15          <Meridian Type="Object">
16            <HUB_CtrlPntList Count="5" Type="Array1" Caption="Hub Contour Controls" I
17              <Value Type="Vector2" Index="0">
18                <x Type="Float">0</x>
19                <y Type="Float">0.006</y>
20              </Value>
21              <Value Type="Vector2" Index="1">
22                <x Type="Float">0.003106277916</x>
23                <y Type="Float">0.006</y>
24              </Value>
25              <Value Type="Vector2" Index="2">
26                <x Type="Float">0.00858</x>
27                <y Type="Float">0.006</y>
28              </Value>
29              <Value Type="Vector2" Index="3">
30                <x Type="Float">0.00858</x>
31                <y Type="Float">0.0114</y>

```



## 2. Software tools      b) TCFD

- **TCFD® = Turbomachinery CFD**
- CFD workflow for turbomachinery simulations
- Commercial software based on OpenFOAM®
- Graphical user interface (GUI) in ParaView
- Developed by CFD Support s.r.o.

Geometry model:

Inlet

Inflow region

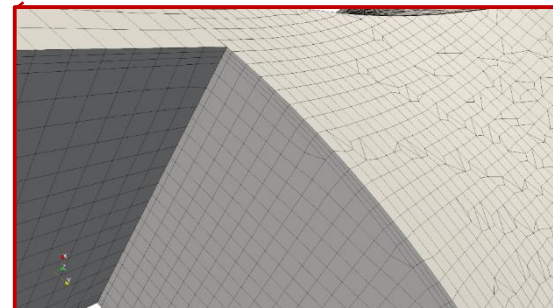
Outflow region

Outlet

Impeller

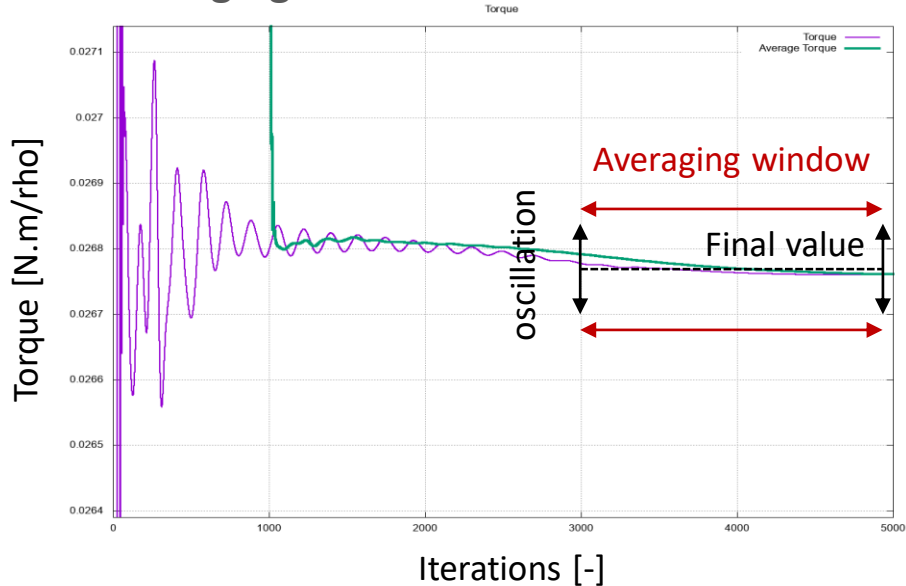
Mesh density:

- 270 000 cells
- Created with snappyHexMesh
- Solver speed ↔ accuracy



## 2. Software tools b) TCFD

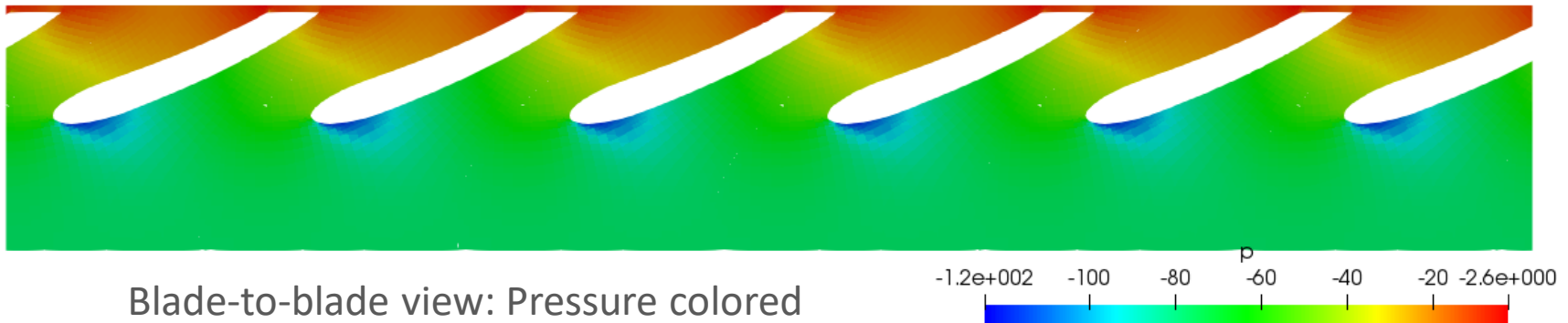
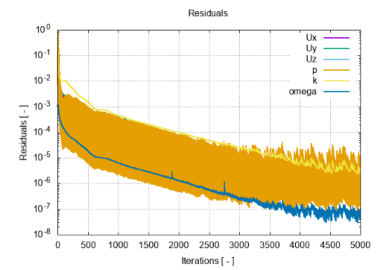
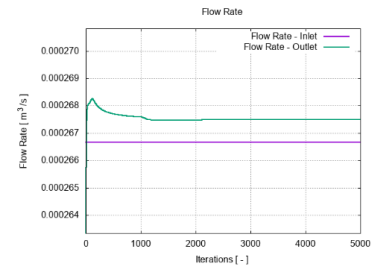
Averaging window:



HTML Report:

### Simulation Stats

|                                        |                                                                            |
|----------------------------------------|----------------------------------------------------------------------------|
| Test Case Name                         | pump-Simulation                                                            |
| Number of Points [ - ]                 | 1                                                                          |
| Machine Type                           | pump                                                                       |
| Rotation Speed [ rad/s ]               | -942.478                                                                   |
| Number of Components [ - ]             | 3                                                                          |
| Mesh Size [ cells ]<br>(details)       | Zulauf : 33 409<br>Impeller : 122 504<br>Ablauf : 71 059<br>Total: 226 972 |
| Average y+ at walls [ - ]<br>(details) | 1.10277                                                                    |
| Wall-clock time [ hh:mm:ss ]           | 00:47:40                                                                   |
| Parallel Processors [ - ]              | 8                                                                          |
| Fluid Name                             | water                                                                      |
| Compressibility                        | incompressible                                                             |

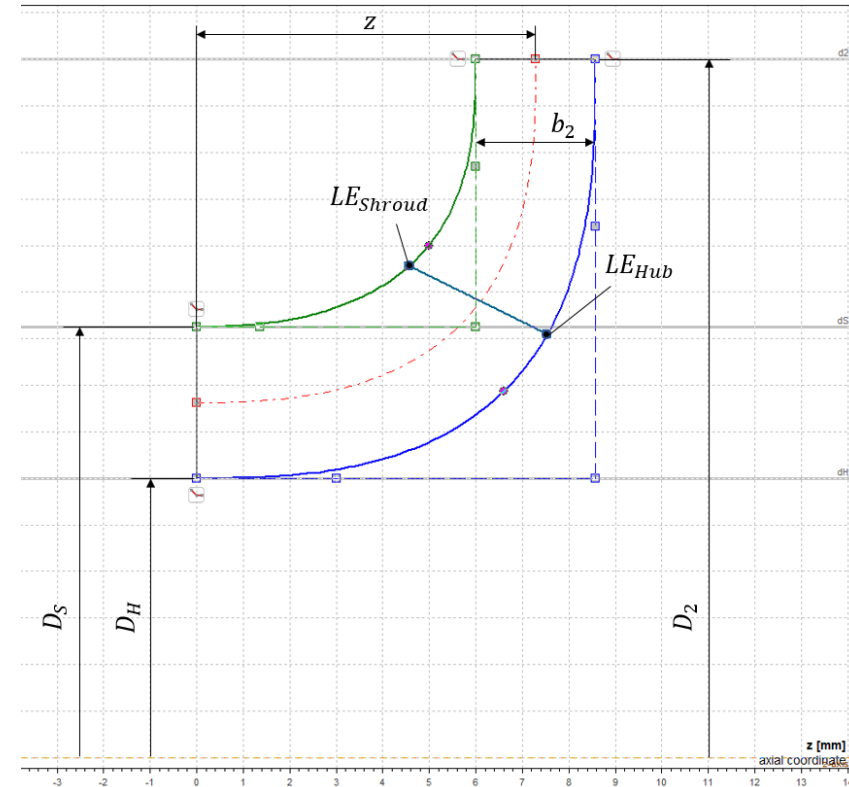


Blade-to-blade view: Pressure colored

## 3. Parameters

- Overall 12 parameters are used

|                    | # | Parameter         | Reference | Minimum | Maximum |
|--------------------|---|-------------------|-----------|---------|---------|
| Main dimensions    | 1 | $D_H$ [mm]        | 12.0      | 9.6     | 14.4    |
|                    | 2 | $D_S$ [mm]        | 18.5      | 14.8    | 22.2    |
|                    | 3 | $b_2$ [mm]        | 2.58      | 2.064   | 3.096   |
|                    | 4 | $D_2$ [mm]        | 30        | 24      | 32      |
| Meridional contour | 5 | $z$ [mm]          | 7.29      | 5.832   | 8.748   |
|                    | 6 | $LE_{Hub}$ [%]    | 58.63     | 53.1    | 64.9    |
|                    | 7 | $LE_{Shroud}$ [%] | 50.16     | 45      | 55      |

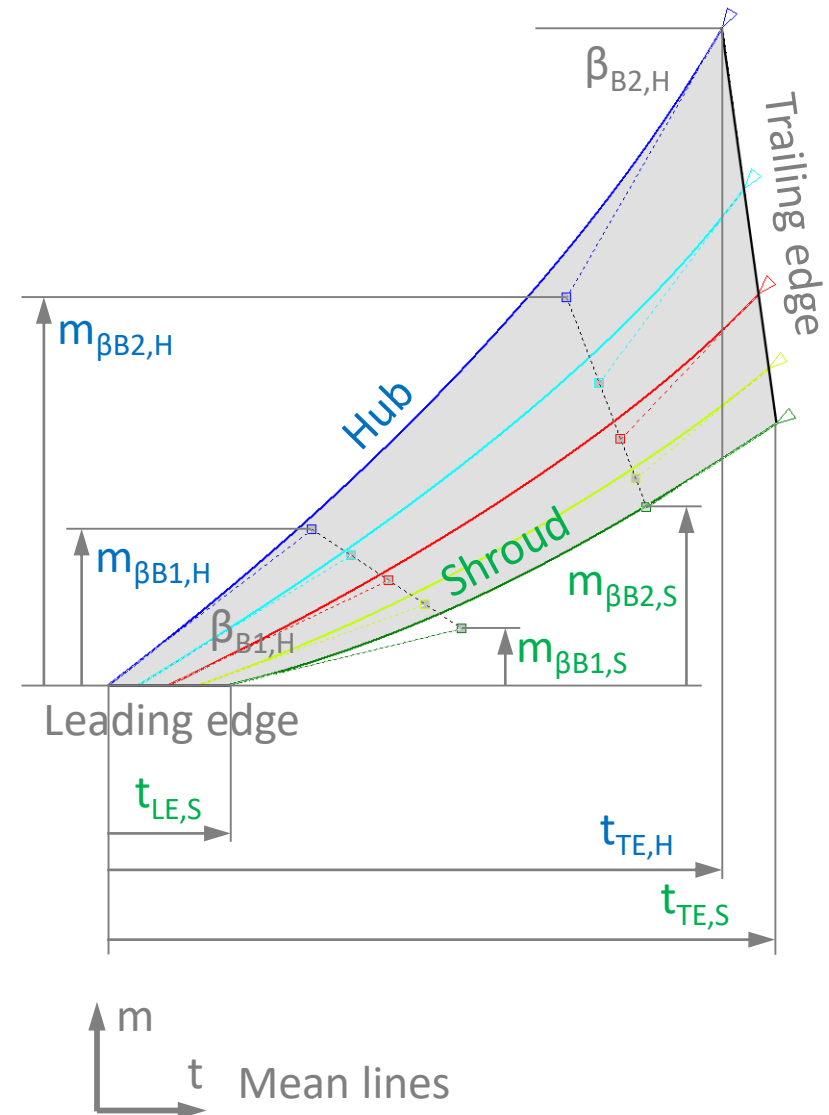
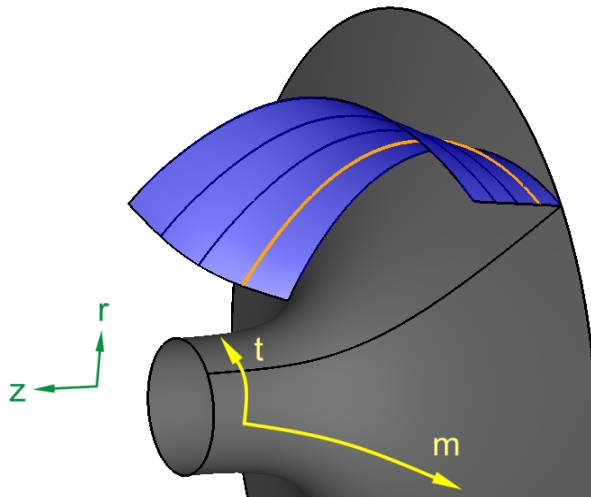


- Minimum / Maximum values:  $\pm 10 \dots 20 \%$
- Maximum  $D_2$  limited by available space



### 3. Parameters

|                  | #  | Parameter            | Reference | Minimum | Maximum |
|------------------|----|----------------------|-----------|---------|---------|
| Blade properties | 8  | $n_{BI}$ [-]         | 5         | 3       | 7       |
|                  | 9  | $\beta_{B1,H}$ [°]   | 19.65     | 15.72   | 23.58   |
|                  | 10 | $\beta_{B2,H}$ [°]   | 28.0      | 22.40   | 33.60   |
| Mean lines       | 11 | $m_{\beta B1,H}$ [%] | 36.15     | 20      | 40      |
|                  | 12 | $m_{\beta B2,H}$ [%] | 66.62     | 60      | 70      |



## 4. Optimization workflow

### Design point

- Flow rate  $Q = 0.96 \text{ m}^3/\text{h}$
- Total pressure difference  $\Delta p_t = 0.87 \text{ bar}$  ( $H = 8.885 \text{ m}$ )
- Rotational speed = 9000 /min
- Water, no pre-swirl

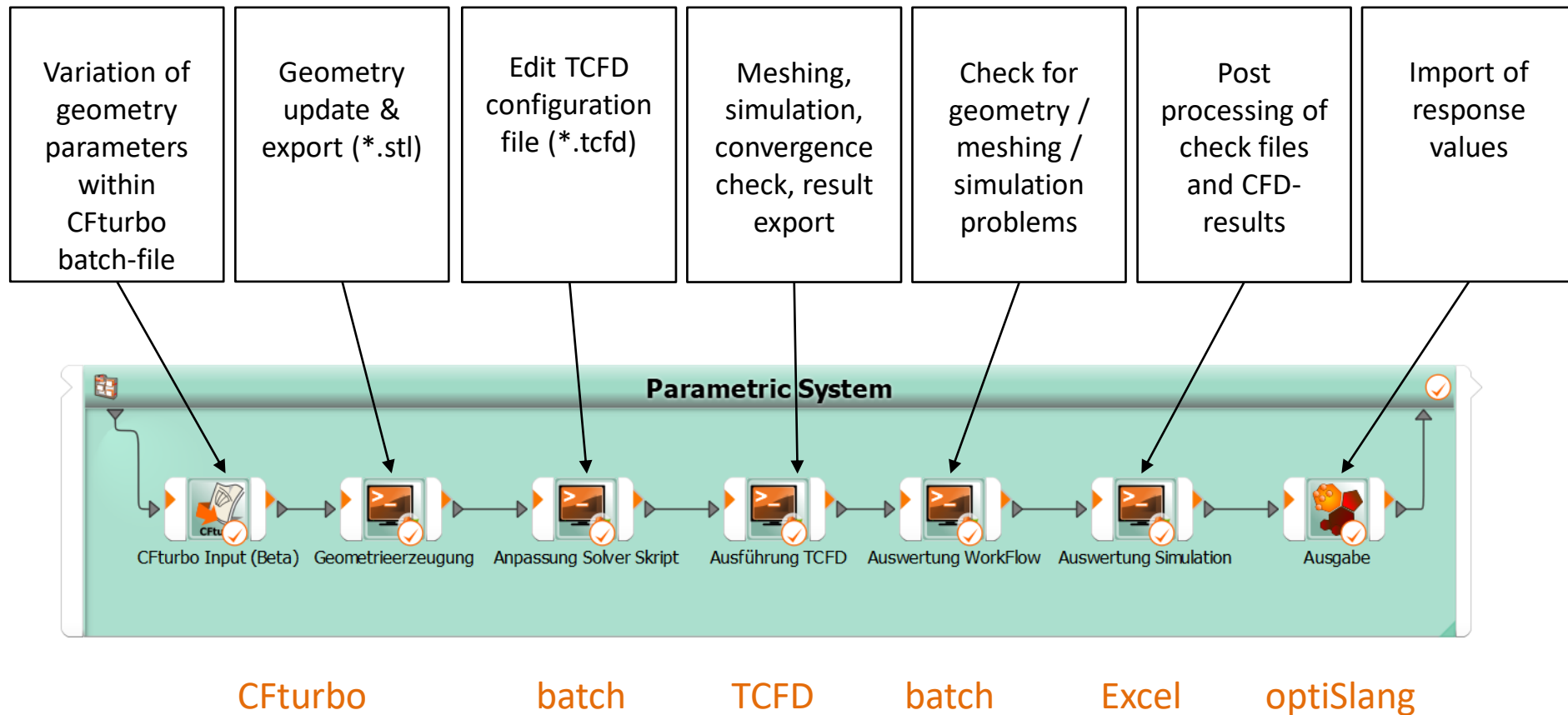
### Objective

- Max. hydraulic efficiency  $\eta_{\text{hydr}}$

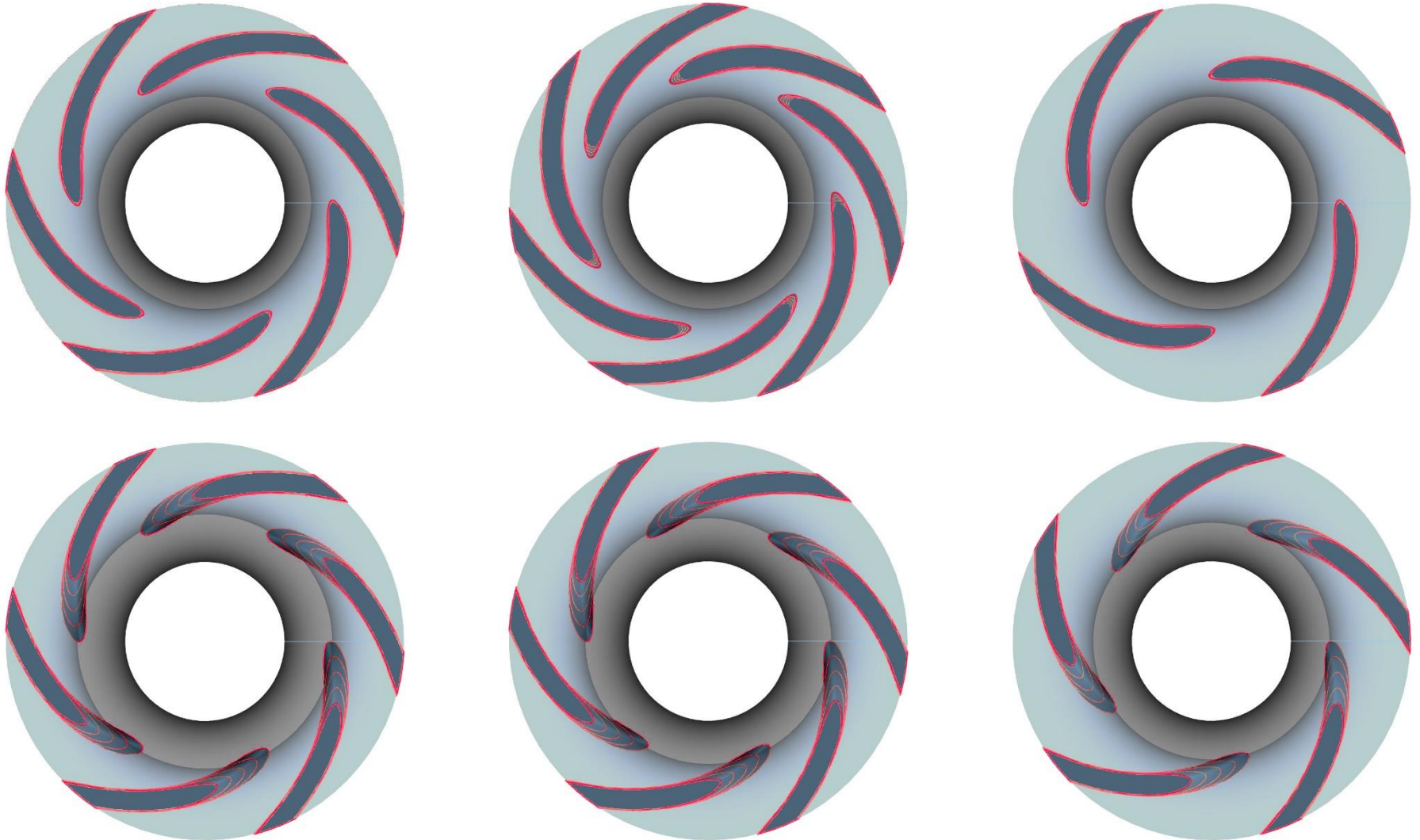
### Constraints

- $P_{\text{hydr}} < 30 \text{ W}$
- Variation of total pressure difference  $\Delta p_t \pm 10\%$

## 4. Optimization workflow



## 5. Results – Some geometry examples



## 5. Results – Sensitivity analysis / Number of samples

### Advanced Latin Hypercube Sampling

|             |               | Samples<br>100 |
|-------------|---------------|----------------|
| Failed      | Geometry      | 10             |
|             | Meshing       | 7              |
|             | Simulation    | 20             |
| Valid       | samples       | 63             |
| Constraints | Valid         | 19             |
|             | Not valid     | 44             |
| CoP         | $\Delta p_t$  | 95.7 %         |
|             | $P_{hydr}$    | 96.6 %         |
|             | $\eta_{hydr}$ | 94.2 %         |



### High variation of results

- $61,27\% \leq \eta_{hydr} \leq 91,15\%$
- 36 samples with low  $\eta_{hydr}$
- Reduction of samples to calculate CoP not possible

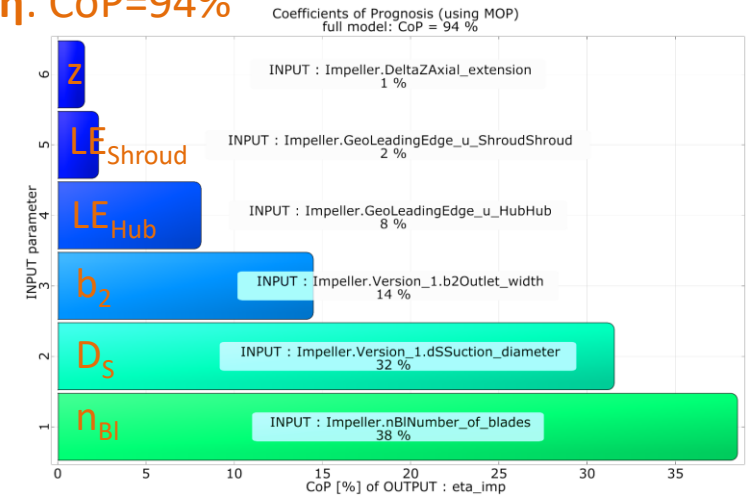
## 5. Results – Sensitivity analysis / Coefficient of Prognosis CoP

$\eta$  hydraulic efficiency (objective)

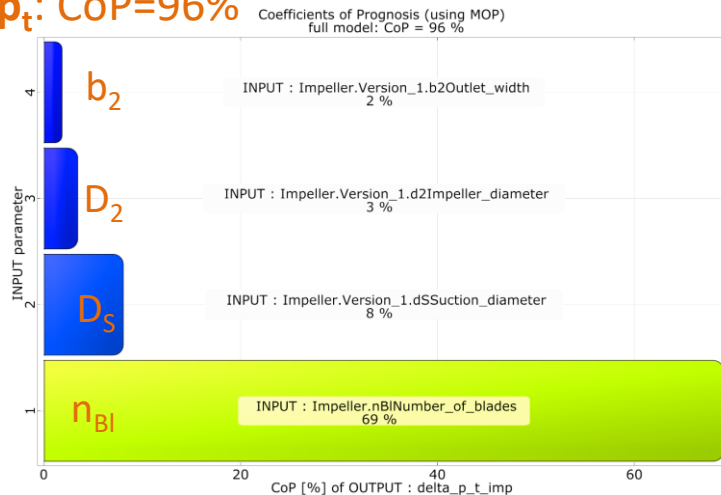
$$\eta = \frac{Q \cdot \Delta p_t}{P}$$

Q Flow rate  
 $\Delta p_t$  Total pressure difference  
 P Power consumption

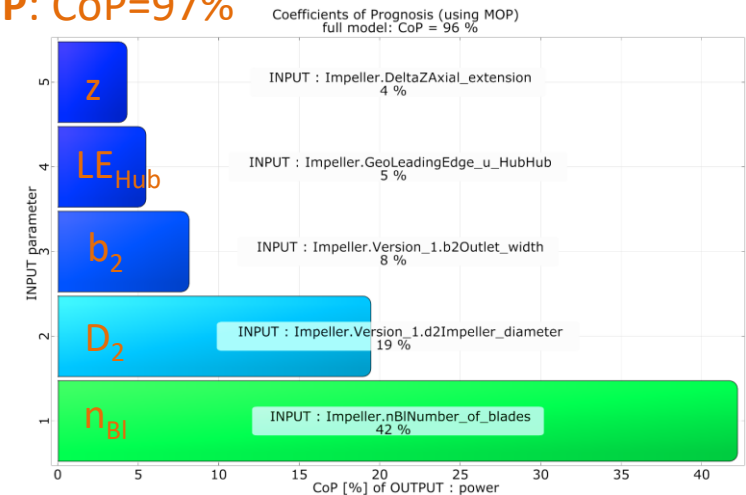
$\eta$ : CoP=94%



$\Delta p_t$ : CoP=96%



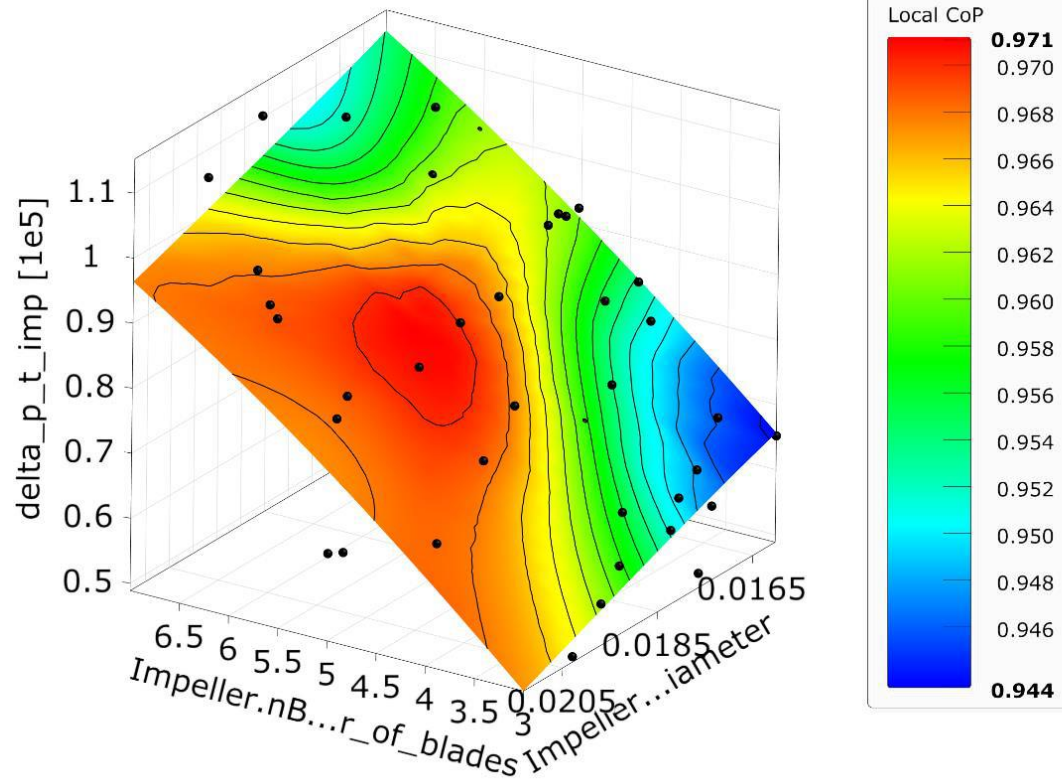
P: CoP=97%





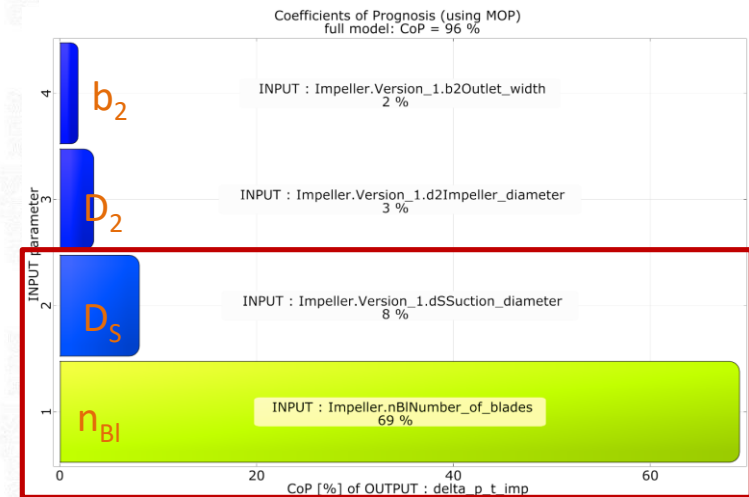
## 5. Results – Sensitivity analysis / Metamodel of Optimal Prognosis MOP

Moving Least Squares approximation of  $\Delta p_{t\_imp}$   
Coefficient of Prognosis = 96 %

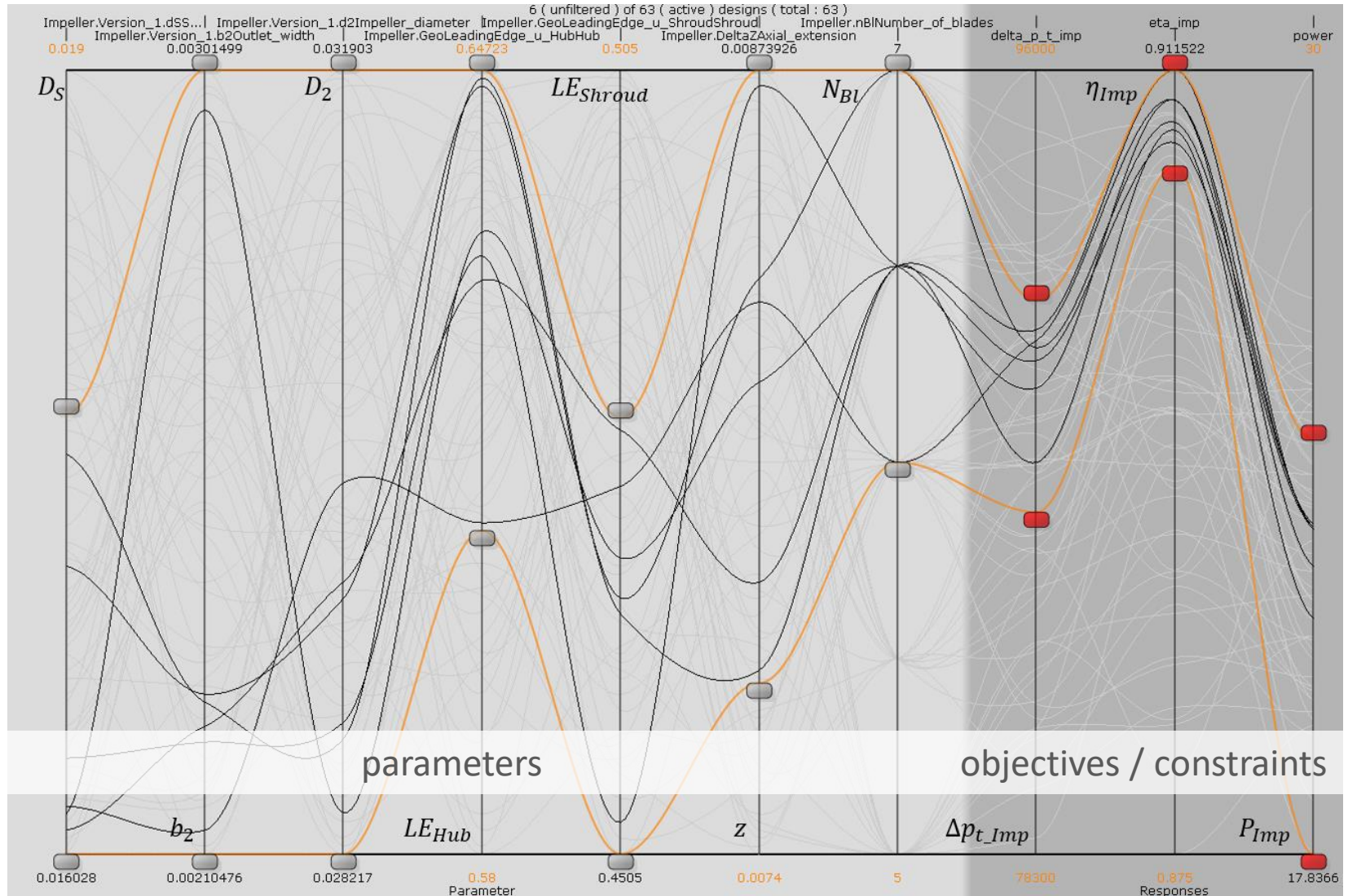


Response surface for  
 $\Delta p_t = f(n_{Bl}, D_s)$

$\Delta p_t$ : CoP=96%



## 5. Results – Sensitivity analysis / Parallel coordinate plot



## 5. Results – Optimization

| Algorithm                                       | Samples | Simulation time              | Simulation time/ sample  | $\eta_{\text{hydr}}$ |
|-------------------------------------------------|---------|------------------------------|--------------------------|----------------------|
| <b>EA</b><br>Evolutionary Algorithm             | 400     | $\approx 235 \text{ h}^*$    | $\approx 35 \text{ min}$ | 92.2 % + 10.2 %      |
| <b>ARSM</b><br>Adaptive Response Surface Method | 260     | $\approx 255 \text{ h}^{**}$ | $\approx 60 \text{ min}$ | 92.2 % + 10.2 %      |

compared to  
initial design

### \* Desktop PC

- 2 x Intel Xeon 3.30 GHz, 8 cores
- 128 GB RAM

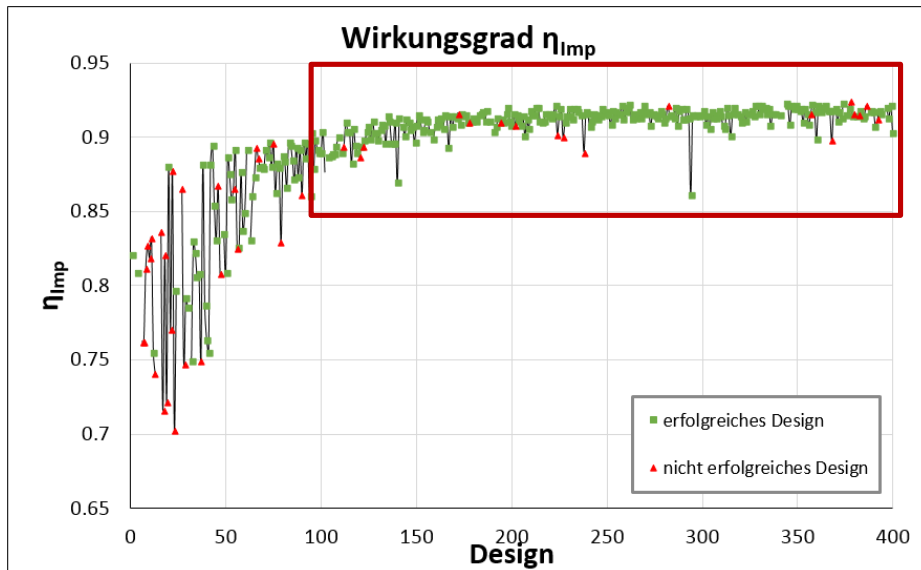
### \*\* Desktop PC

- 2 x Intel Xeon 3.07 GHz, 6 cores
- 32 GB RAM

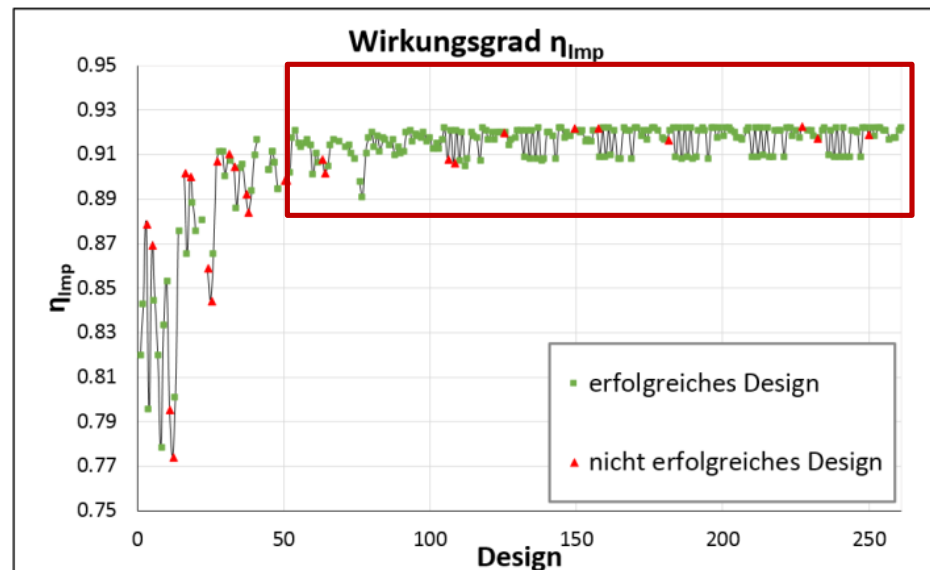
## 5. Results – Optimization

|             | $D_H$<br>[mm] | $D_S$<br>[mm] | $D_2$<br>[mm] | $n_{Bl}$<br>[mm] | $z$<br>[mm] | $\beta_{B1,H}$<br>[°] | $\beta_{B2,H}$<br>[°] | $\Delta p_t$<br>[bar] | $P$<br>[ W] | $\eta_{hydr}$<br>[%] |
|-------------|---------------|---------------|---------------|------------------|-------------|-----------------------|-----------------------|-----------------------|-------------|----------------------|
| <b>EA</b>   | 12.12         | 15.98         | 29.71         | 6                | 7.28        | 18.51                 | 23.73                 | 0.897                 | 25.94       | 92.2                 |
| <b>ARSM</b> | 12.00         | 15.95         | 30.00         | 5                | 7.09        | 19.65                 | 28.00                 | 0.904                 | 26.15       | 92.2                 |

**EA:**



**ARSM:**



## 5. Results – Optimization

Reference

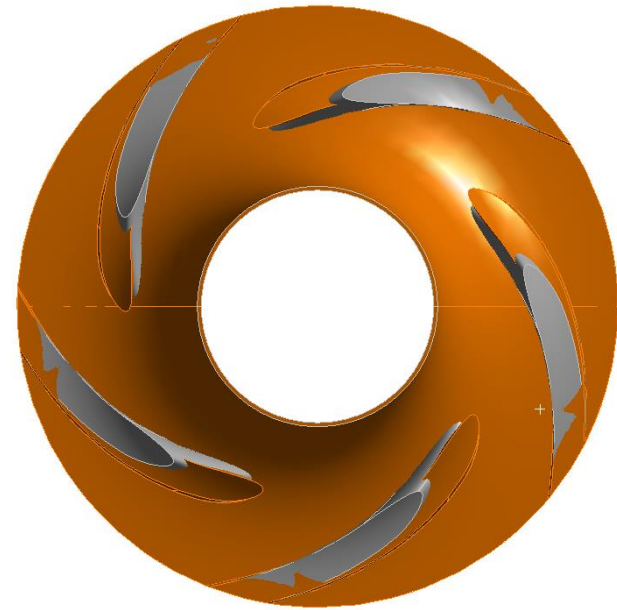
ARSM

Reference

EA

ARSM

EA





## 6. Conclusion, outlook

- Optimization process CFturbo + TCFD + optiSLang successfully tested
- CFturbo initial design can be used as very reasonable starting point („pre-optimized“) to save optimization time
- Geometry simplifications necessary to save optimization time  
→ segment model
- High CoP of efficiency due to high variation of results
- Different geometric designs as result of EA and ARSM  
→ more than 1 optimum with similar efficiency
- Next steps:
  - Use metamodel for indirect optimization
  - Optimization of other components (volute, diffusor) of pump with optimized impeller

Thanks to Dynardo (optiSLang) and CFD Support (TCFD) for licenses and support!