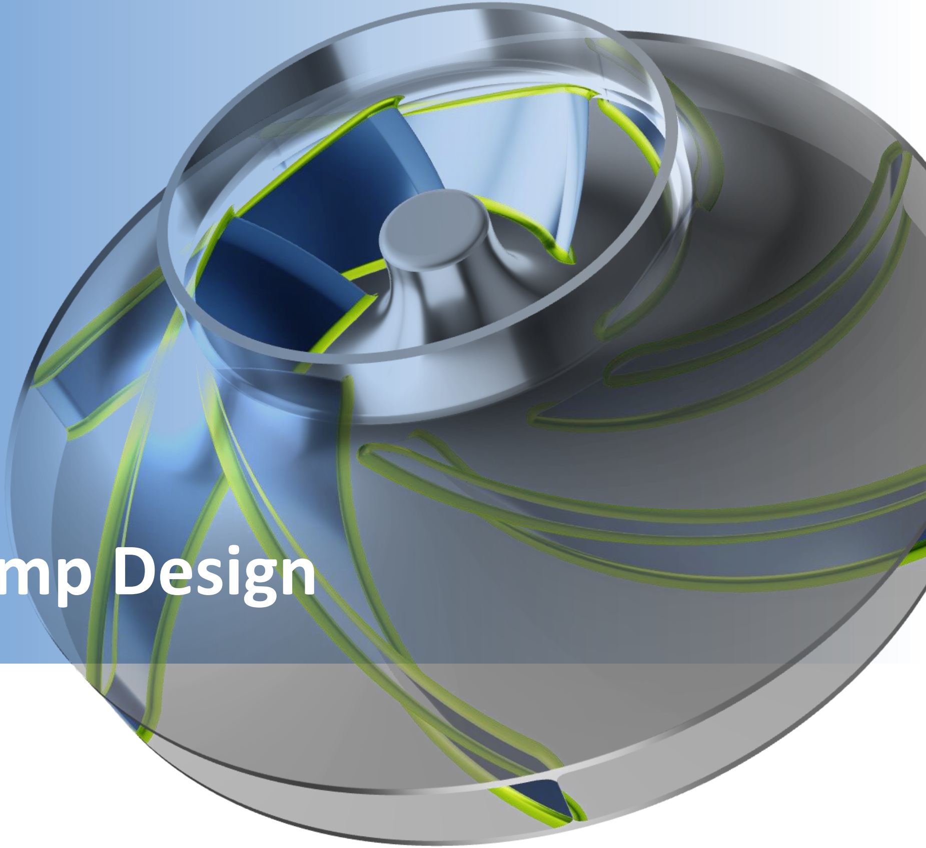
High-Efficiency Circulator Pump Design



Creating an Innovative Workflow

Motivation | Energy Efficiency Index

- Starting from January 1, 2013, circulators must comply with European regulation 641/2009, part of the ecodesign policy of the European Union

exemplary picture

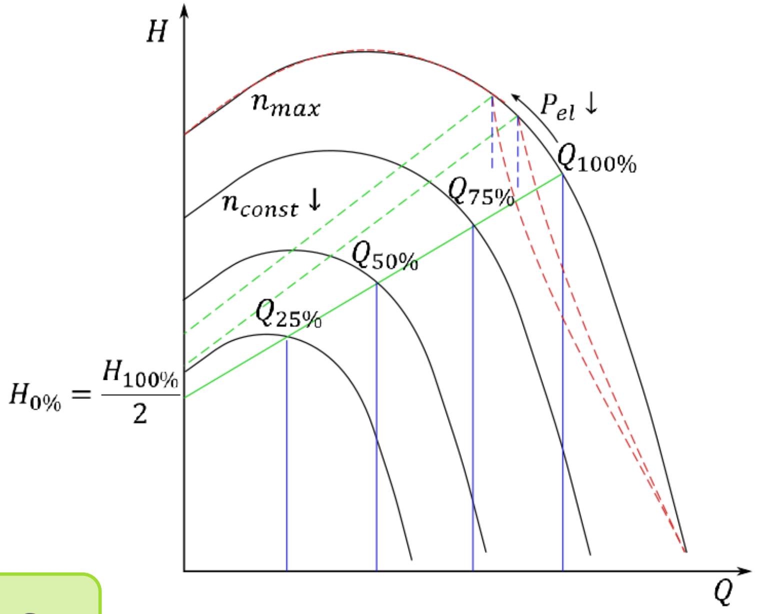
Motivation | Energy Efficiency Index

- Starting from January 1, 2013, circulators must comply with European regulation 641/2009, part of the ecodesign policy of the European Union
- Minimum value of Energy Efficiency Index (EEI) is prescribed
  - EEI also takes into account part load operating power consumption and motor characteristics

exemplary picture

Motivation | Energy Efficiency Index

- Starting from January 1, 2013, circulators must comply with European regulation 641/2009, part of the ecodesign policy of the European Union
- Minimum value of Energy Efficiency Index (EEI) is prescribed
  - EEI also takes into account part load operating power consumption and motor characteristics
  - Calculated by comparing the average (measured) power consumption of the circulator across a load profile against a predefined reference power input



$$EEI = \frac{0.06P_{L,100\%} + 0.15P_{L,75\%} + 0.35P_{L,50\%} + 0.44P_{L,25\%}}{P_{ref}} C_{20\%}$$

Motivation | Energy Efficiency Index

- Pump selection depends on system components which are varying until late in product development
- This means, pump selection has to be done *fast*, at the end of the product development process

→ Aim: Development of the hydraulic part of a tool chain to minimize the EEI of a pump

→ Idea: Pump selection via surrogate model generated by impeller CFD simulations

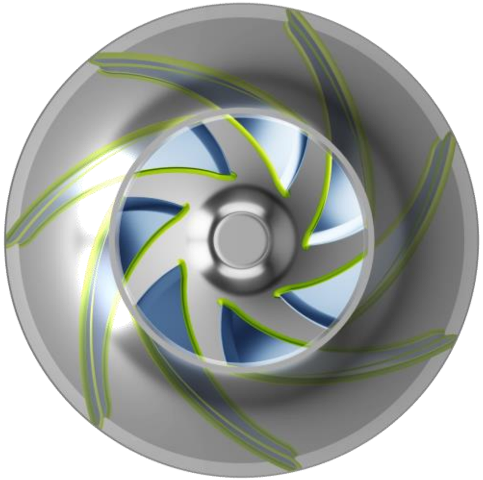
Modeling of a parametric impeller → Connection to SimScale to allow computation → DoE of the impeller → Generation of surrogate model(s) → Optimization with surrogate

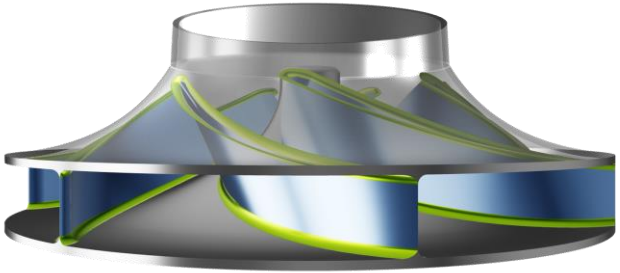
Project Steps | CAD Modeling and Variation

CAESES

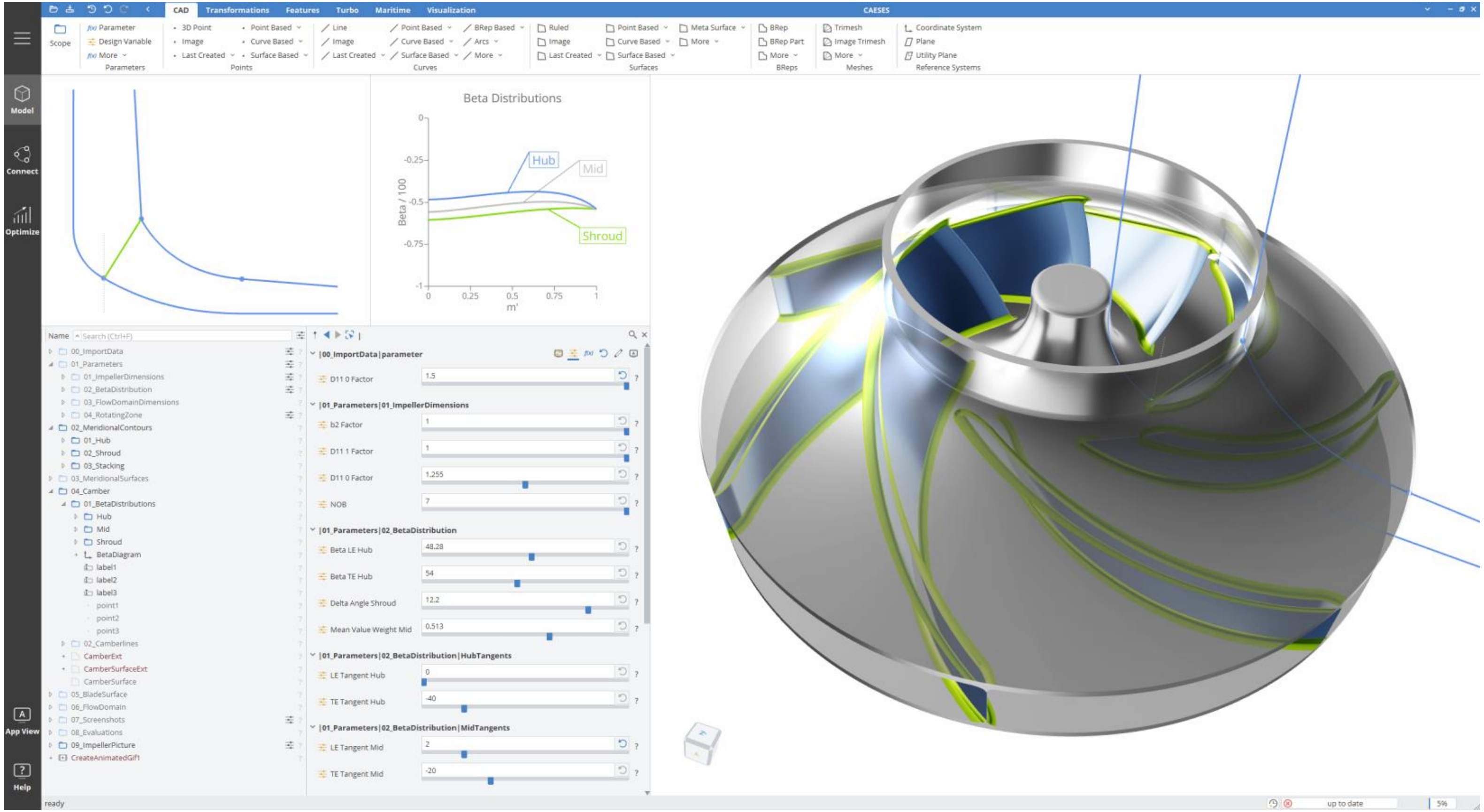
CAD | AUTOMATION | OPTIMIZATION

- SMARTER GEOMETRIES
- EFFICIENT PARAMETERIZATION
- SIMULATION-READY
- 100% ROBUST
- CONSTRAINT MANAGEMENT

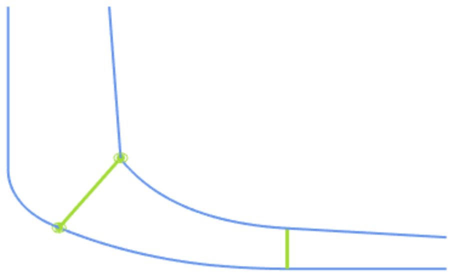




Project Steps | CAD Modeling and Variation

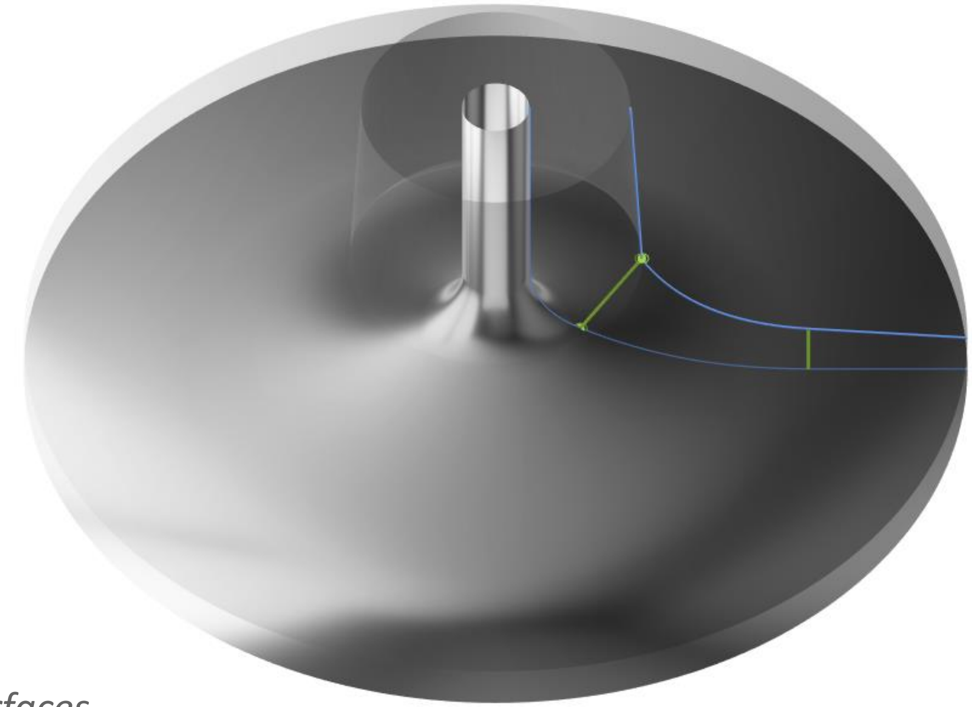


CAD Modeling | Modeling Steps



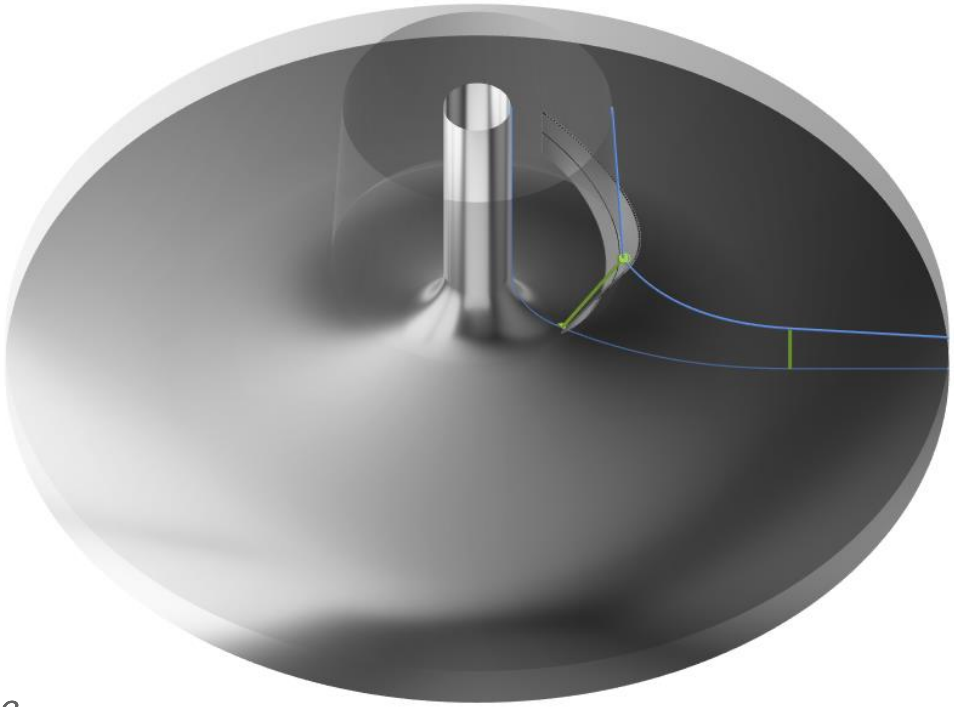
1. *Meridional contours*

CAD Modeling | Modeling Steps



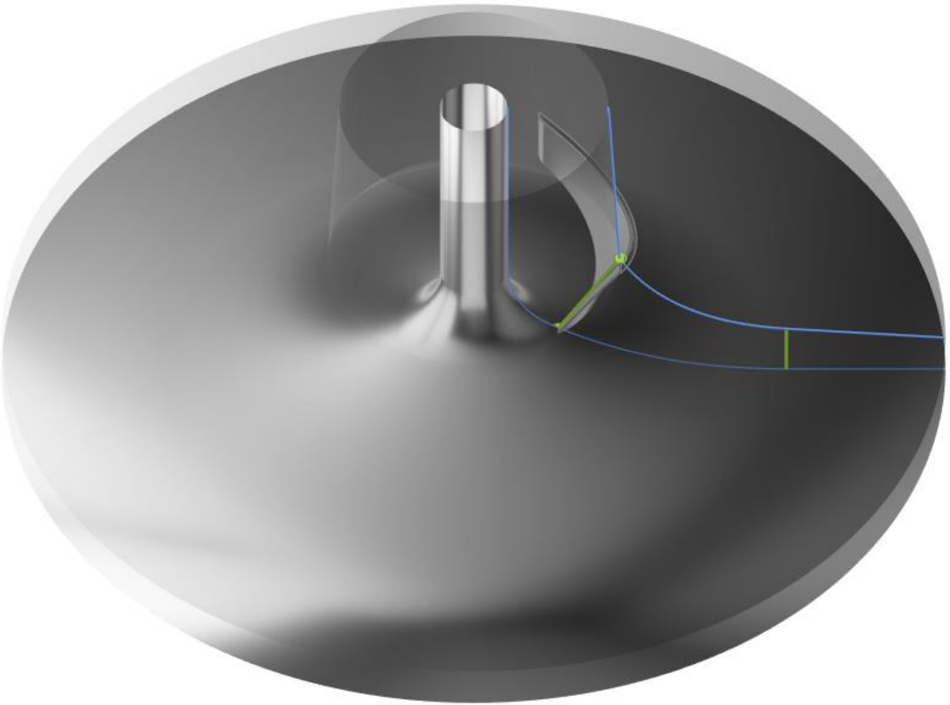
2. *Hub and shroud surfaces*

CAD Modeling | Modeling Steps



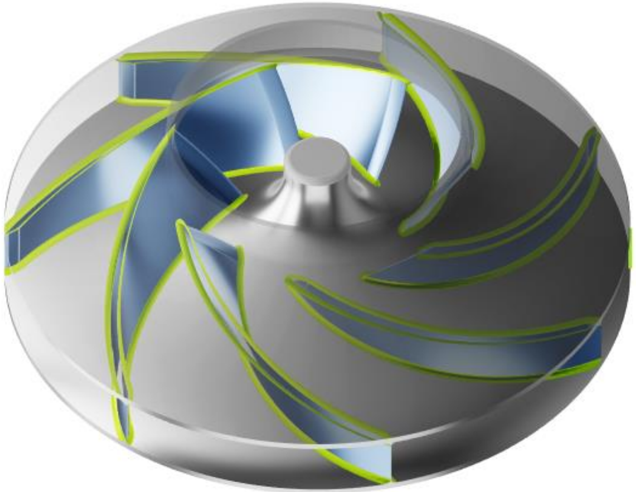
3. *Mean camber surface*

CAD Modeling | Modeling Steps



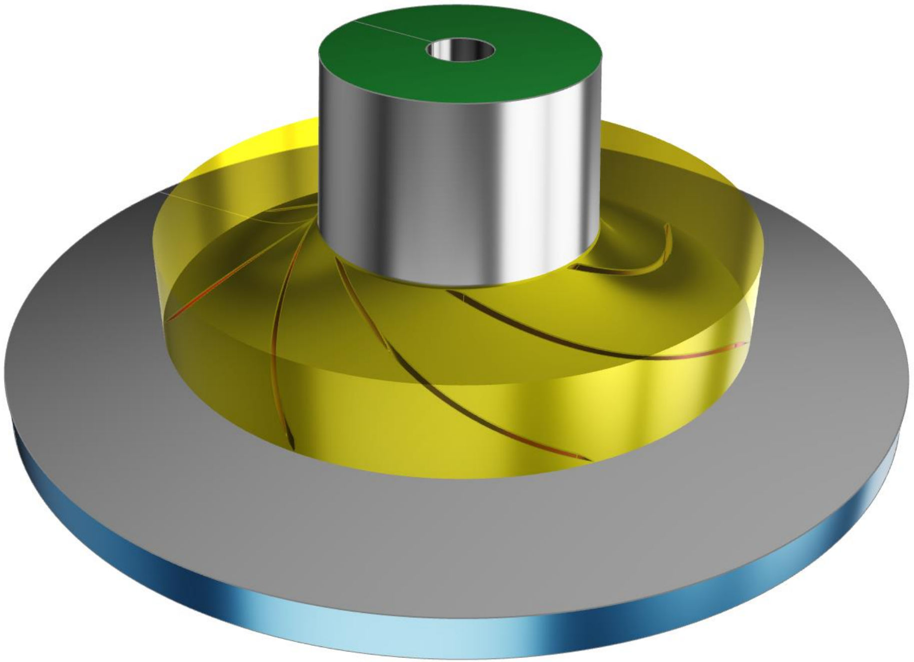
4. *Blade solid*

CAD Modeling | Modeling Steps



5. *Finalizing*

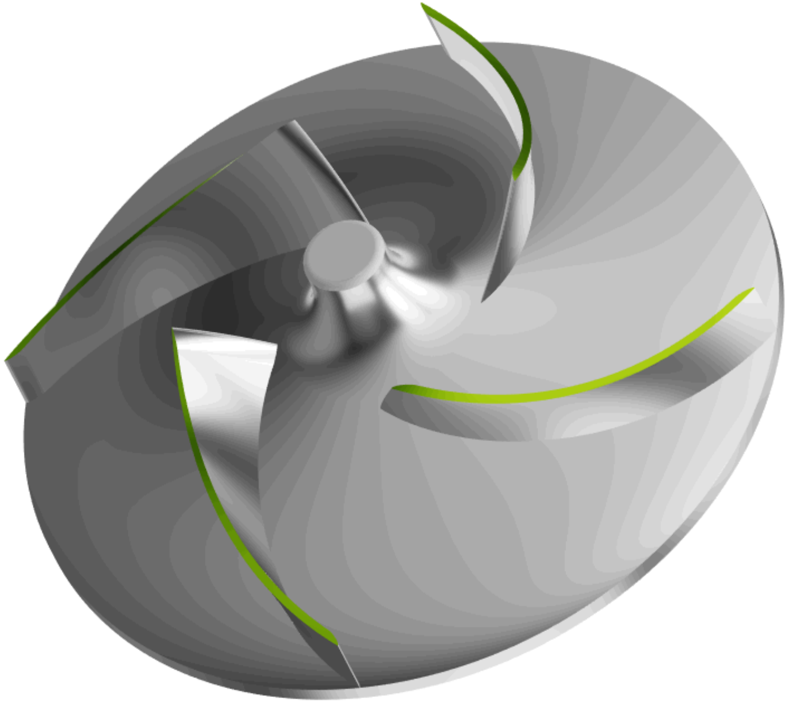
CAD Modeling | Modeling Steps



6. *Flow domain*

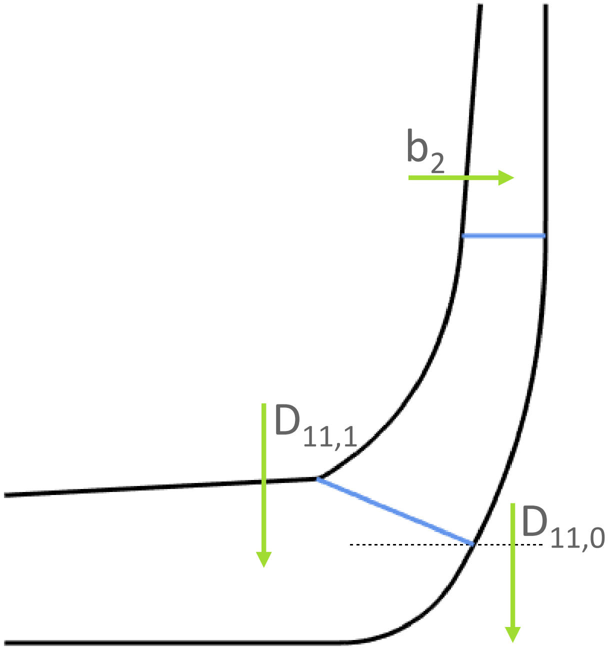
Geometry Variation | Design Variables

- Number of blades



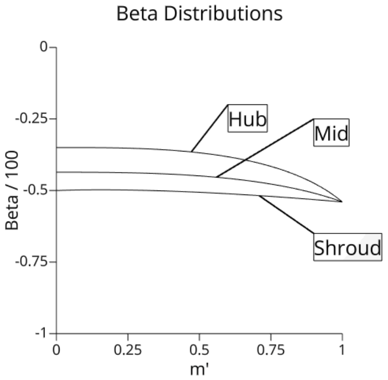
Geometry Variation | Design Variables

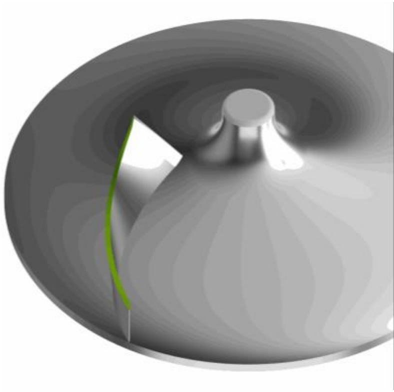
- Number of blades
- Meridional contours:
  - 3 parameters

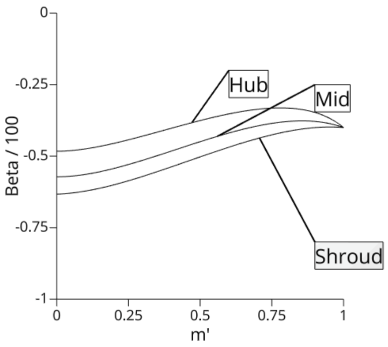


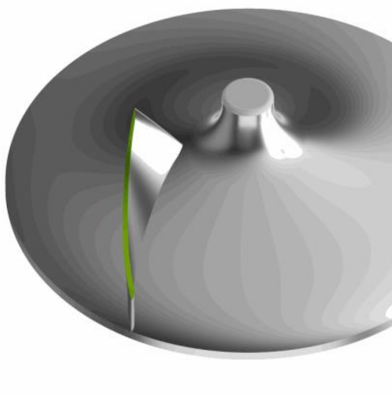
Geometry Variation | Design Variables

- Number of blades
- Meridional contours:
  - 3 parameters
- Blade angle distributions:
  - 2 parameters for LE and TE blade angle



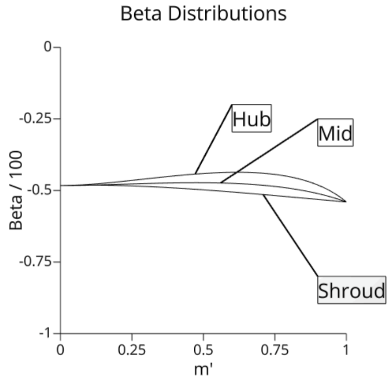


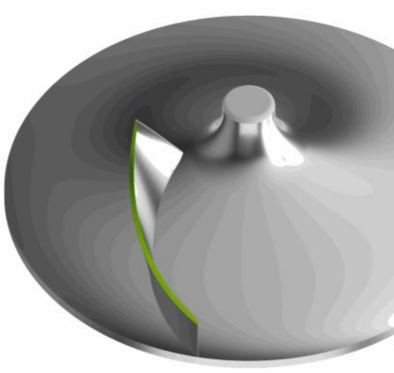


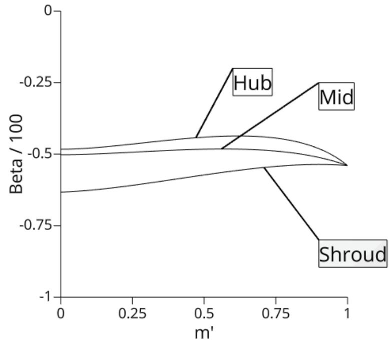


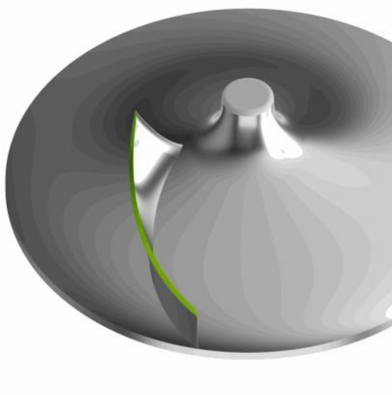
Geometry Variation | Design Variables

- Number of blades
- Meridional contours:
  - 3 parameters
- Blade angle distributions:
  - 2 parameters for LE and TE blade angle
  - 2 parameters for hub to shroud variation of LE blade angle





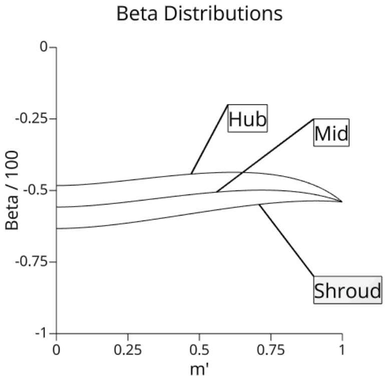


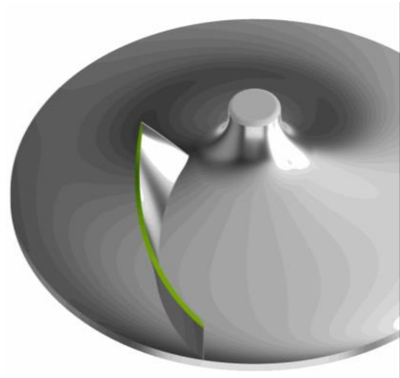


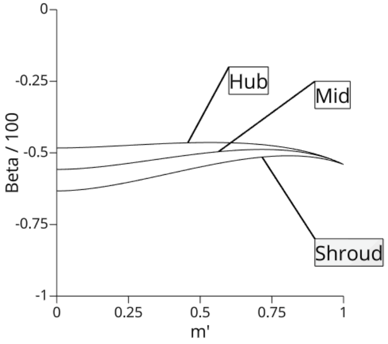
Geometry Variation | Design Variables

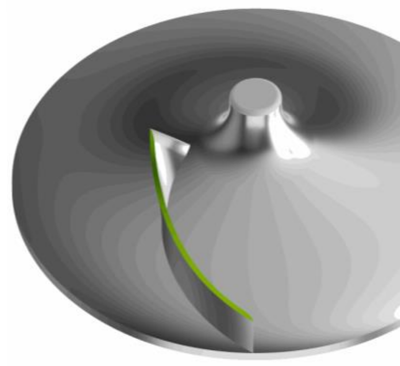
- Number of blades
- Meridional contours:
  - 3 parameters
- Blade angle distributions:
  - 2 parameters for LE and TE blade angle
  - 2 parameters for hub to shroud variation of LE blade angle
  - 6 parameters for shape control of beta functions between LE and TE

→ *14 parameters in total*









Project Steps | CFD Automation

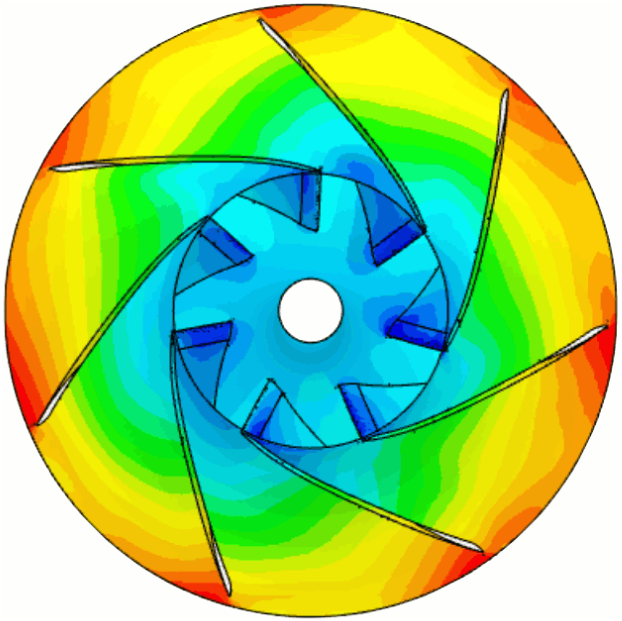
CAESES

CAD

AUTOMATION

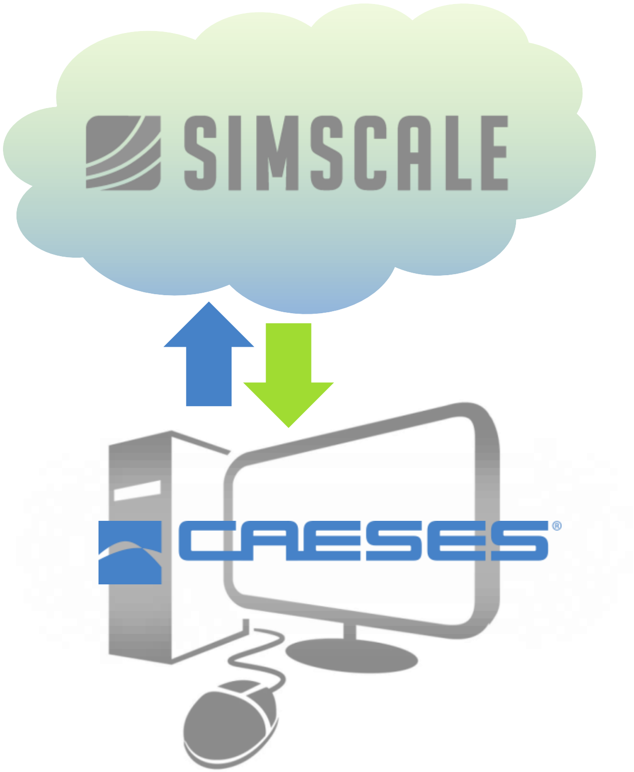
OPTIMIZATION

SIMSCALE



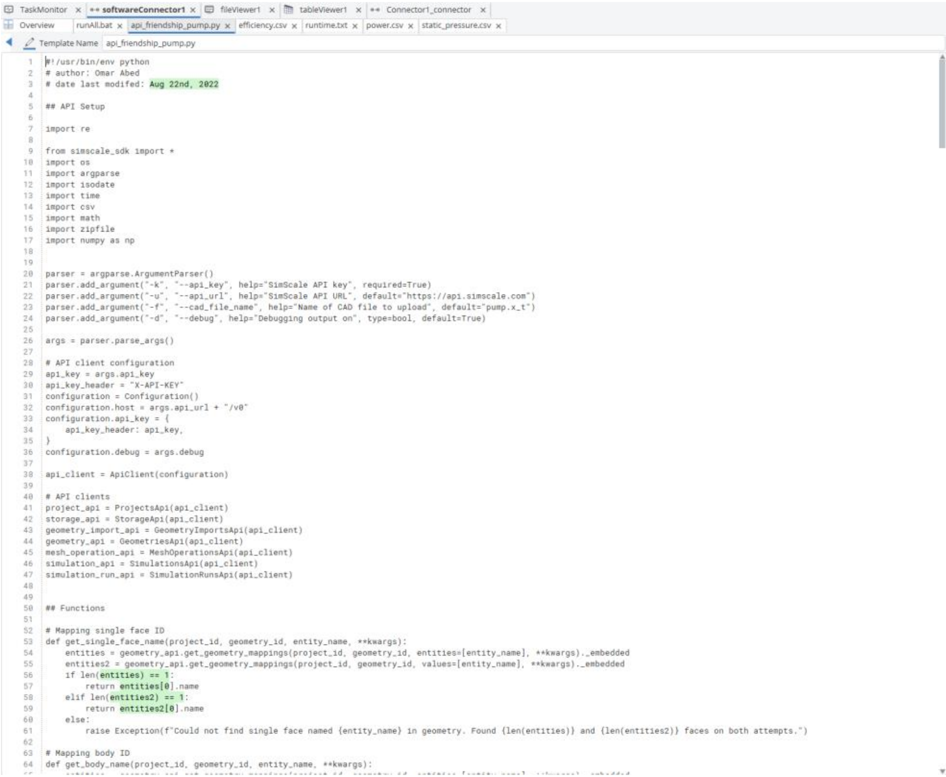
CFD Automation | CFD in the Cloud

- CAESES runs on the local workstation, while SimScale runs in the cloud



CFD Automation | CFD in the Cloud

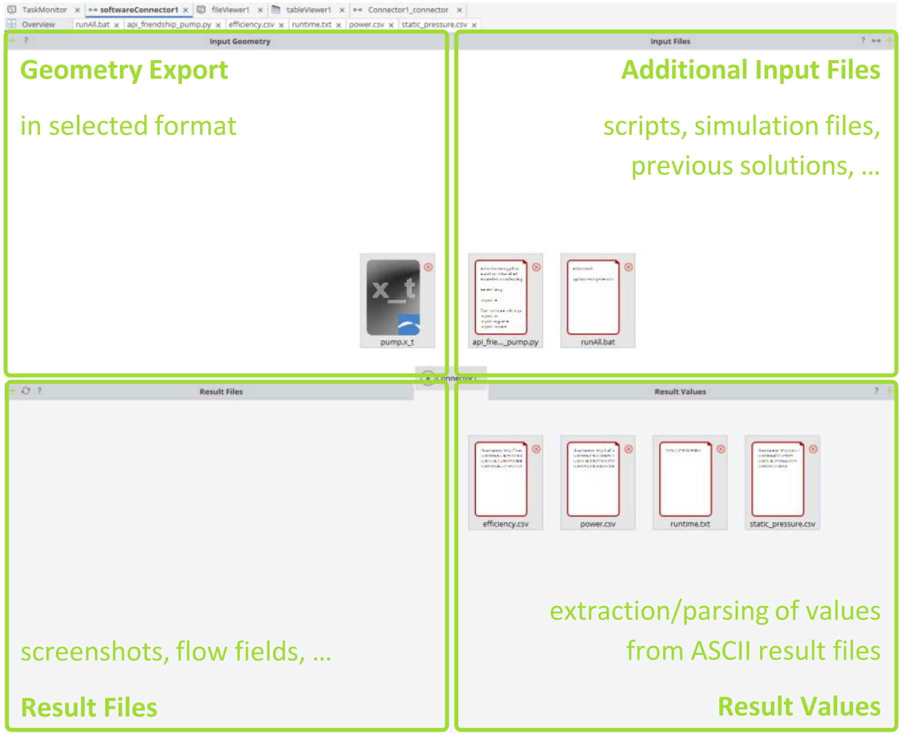
- CAESES runs on the local workstation, while SimScale runs in the cloud
- Control of the SimScale API via a Python script
  - Import geometry to the SimScale platform
  - Set up the case (boundary conditions, mesh settings, solver settings, etc.)
  - Run computation
  - Download result files to the local workstation
- 3 flow rates are computed in parallel: 0.7, 0.85, 1.1 x Q/Q_{opt}



CFD Automation | Exports and Imports

- Exports:
  - Flow domain geometry in Parasolid format
  - Python script
  - Batch script to run Python with the necessary arguments

- Imports:
  - CSV files for head, efficiency, and power values at all 3 flow rates
  - Text file with computation runtime



Project Steps | Optimization

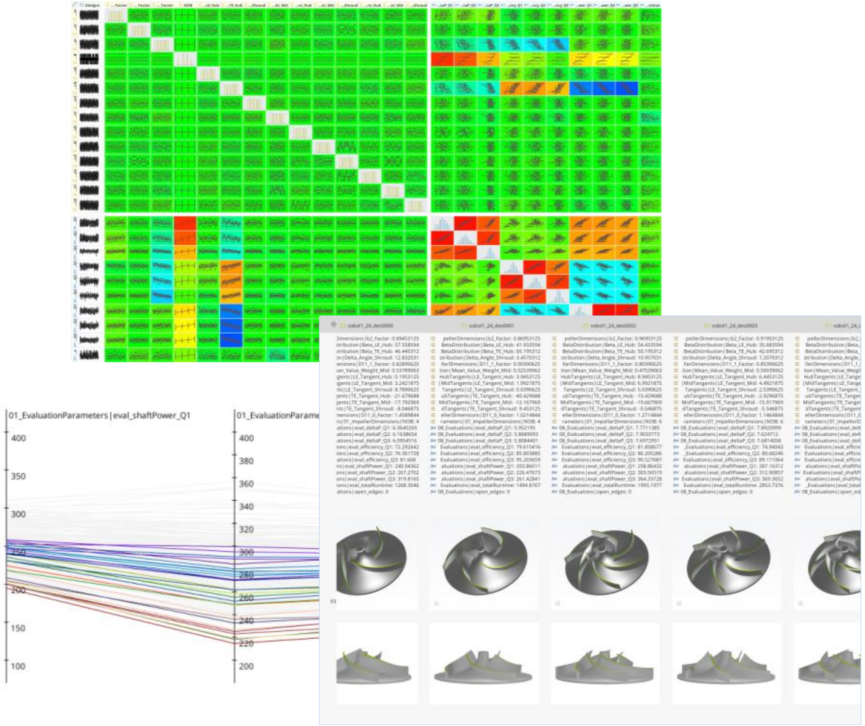
CAESES®

CAD

AUTOMATION

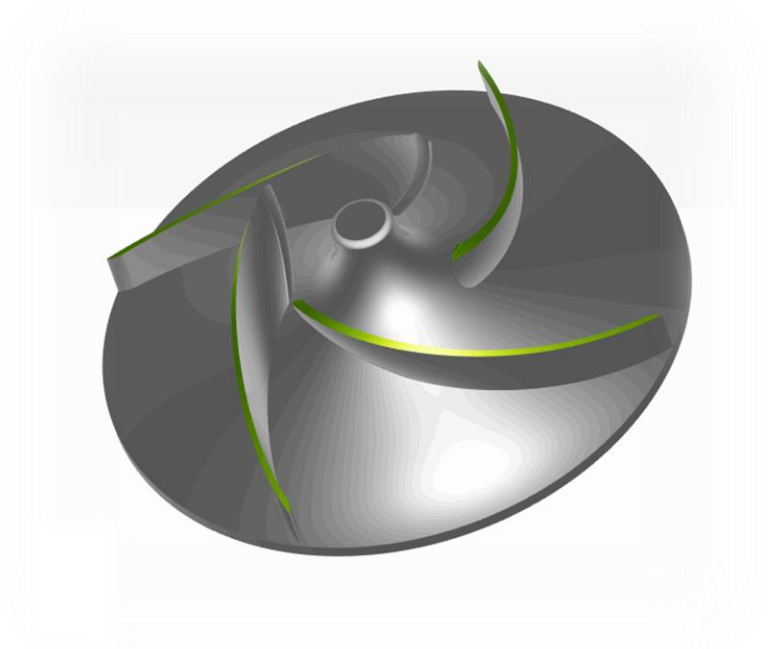
OPTIMIZATION

- DESIGN STUDIES
- MULTI-OBJECTIVE RUNS
- RESPONSE SURFACES
- 2D CHARTS AND CORRELATIONS
- POST-PROCESSING

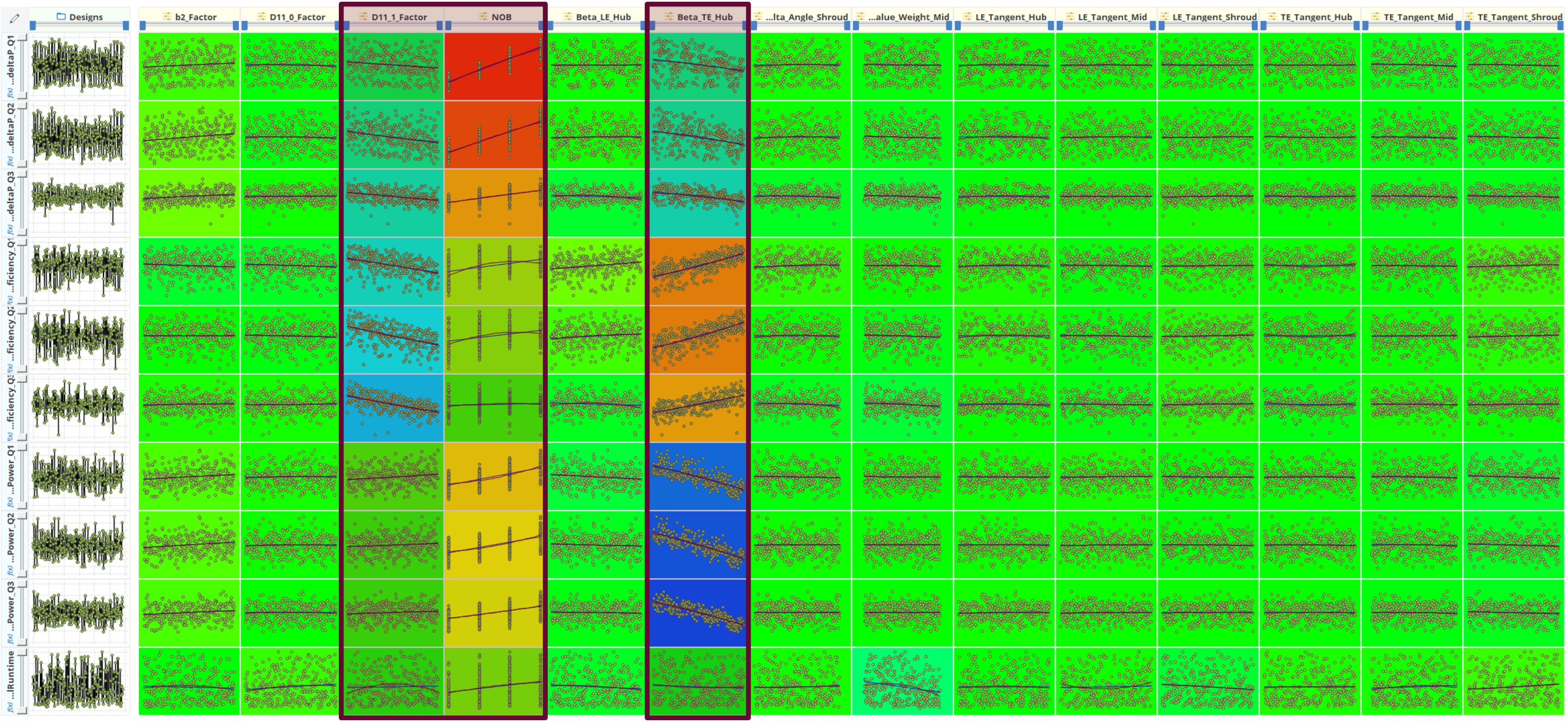


Optimization | DoE Setup

- Sobol sequence with the 14 selected design variables
- ~300 impeller variants simulated with 3 flow rates each (~900 simulations)
- Cumulative simulation runtime: 592.6 hours (~25 days)
- Actual parallelized runtime: 42.4 hours
- Average # of simulations in parallel / parallelization factor: 14
- Computational cost: 3,084 core hours (CHs) used (~10.3 CHs per design variant)

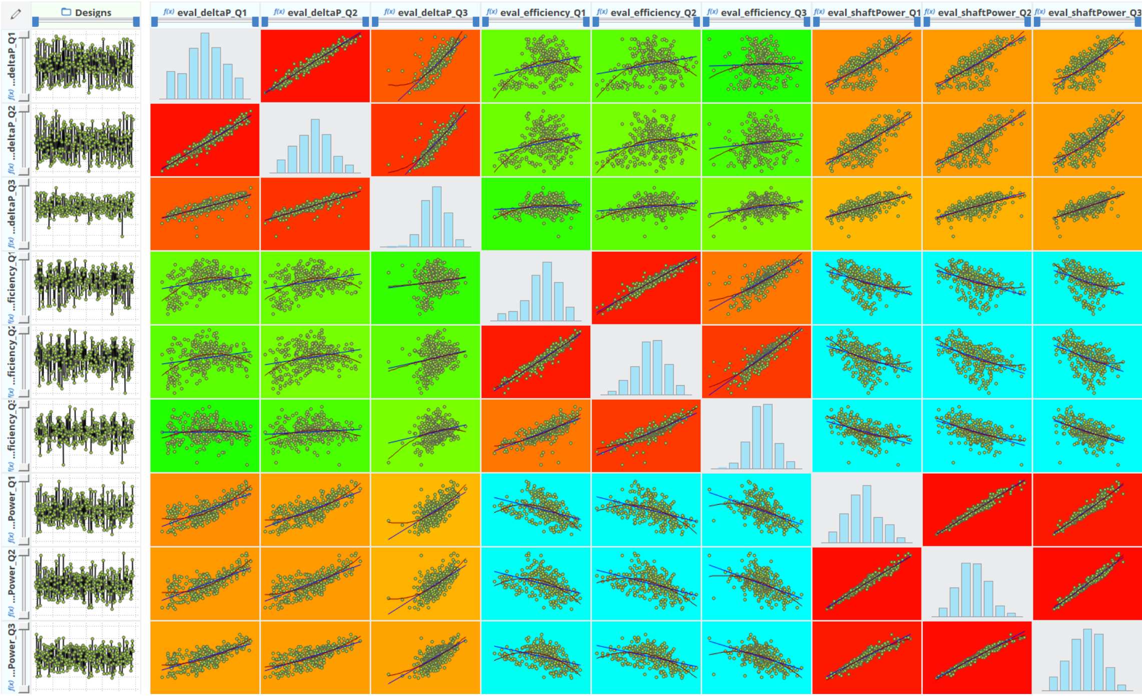


Optimization | DoE Results



Optimization | DoE Results

- Performance values at all 3 flow rates are well correlated in the considered range (0.7-1.1 x Q/Q_{opt})



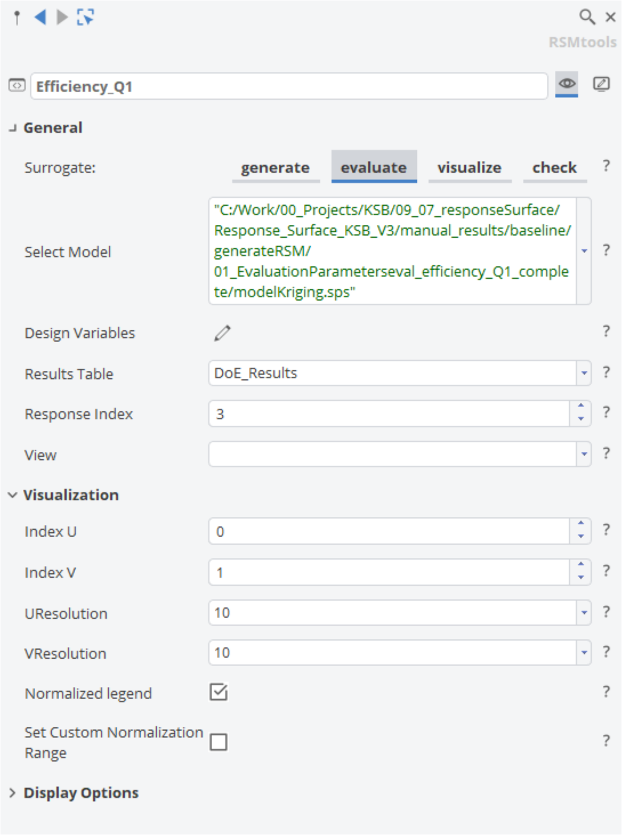
Optimization | Surrogate Models

- Surrogate models created in a separate project using imported design result table from DoE

	b2_Factor	D11_0_Factor	D11_1_Factor	NOB	Beta_LE_Hub	Beta_TE_Hub	Delta_Angle_Shroud	Mean_Value_Weight_Mid	LE_Tangent_Hub	LE
sobol1_14_des0000	0.9	1.25	0.9	6	47.5	55	7.5	0.5	5	
sobol1_14_des0001	0.95	1.125	0.95	6	41.25	62.5	3.75	0.475	7.5	
sobol1_14_des0003	0.875	1.0625	0.975	5	44.375	58.75	1.875	0.5375	1.25	
sobol1_14_des0004	0.975	1.3125	0.875	7	56.875	43.75	9.375	0.4875	6.25	
sobol1_14_des0005	0.925	1.1875	0.825	6	38.125	51.25	5.625	0.5125	8.75	
sobol1_14_des0006	0.825	1.4375	0.925	4	50.625	66.25	13.125	0.4625	3.75	
sobol1_14_des0008	0.9375	1.03125	0.8125	5	55.3125	64.375	2.8125	0.51875	5.625	
sobol1_14_des0009	0.9875	1.40625	0.8625	5	36.5625	56.875	14.0625	0.49375	8.125	
sobol1_14_des0010	0.8875	1.15625	0.9625	7	49.0625	41.875	6.5625	0.54375	3.125	
sobol1_14_des0011	0.8625	1.34375	0.8875	6	39.6875	68.125	8.4375	0.53125	1.875	
sobol1_14_des0012	0.9625	1.09375	0.9875	5	52.1875	53.125	0.9375	0.48125	6.875	
sobol1_14_des0013	0.9125	1.46875	0.9375	4	45.9375	45.625	12.1875	0.50625	9.375	
sobol1_14_des0014	0.8125	1.21875	0.8375	6	58.4375	60.625	4.6875	0.45625	4.375	
sobol1_14_des0015	0.81875	1.42188	0.85625	4	46.7188	65.3125	6.09375	0.484375	5.3125	
sobol1_14_des0016	0.91875	1.17188	0.95625	6	59.2188	50.3125	13.5938	0.534375	0.3125	
sobol1_14_des0017	0.96875	1.29688	0.90625	7	40.4688	42.8125	2.34375	0.459375	2.8125	
sobol1_14_des0018	0.86875	1.04688	0.80625	5	52.9688	57.8125	9.84375	0.509375	7.8125	
sobol1_14_des0019	0.89375	1.48438	0.93125	5	37.3438	54.0625	4.21875	0.521875	6.5625	
sobol1_14_des0020	0.99375	1.23438	0.83125	6	49.8438	69.0625	11.7188	0.471875	1.5625	
sobol1_14_des0021	0.94375	1.35938	0.88125	6	43.5938	61.5625	0.46875	0.546875	4.0625	
sobol1_14_des0022	0.84375	1.10938	0.98125	4	56.0938	46.5625	7.96875	0.496875	9.0625	
sobol1_14_des0023	0.83125	1.14063	0.96875	6	38.9063	55.9375	12.6563	0.490625	5.9375	
sobol1_14_des0024	0.93125	1.39063	0.86875	4	51.4063	40.9375	5.15625	0.540625	0.9375	
sobol1_14_des0025	0.98125	1.01563	0.81875	5	45.1563	48.4375	8.90625	0.465625	3.4375	
sobol1_14_des0027	0.85625	1.20313	0.84375	7	42.0313	44.6875	14.5313	0.503125	7.1875	
sobol1_14_des0028	0.95625	1.45313	0.94375	5	54.5313	59.6875	7.03125	0.453125	2.1875	
sobol1_14_des0029	0.90625	1.07813	0.99375	5	35.7813	67.1875	10.7813	0.528125	4.6875	
sobol1_14_des0030	0.80625	1.32813	0.89375	6	48.2813	52.1875	3.28125	0.478125	9.6875	
sobol1_14_des0031	0.809375	1.17969	0.940625	5	41.6406	58.2813	8.67188	0.514063	2.65625	
sobol1_14_des0032	0.909375	1.42969	0.840625	6	54.1406	43.2813	1.17188	0.464063	7.65625	
sobol1_14_des0033	0.959375	1.05469	0.890625	7	35.3906	50.7813	12.4219	0.539063	5.15625	
sobol1_14_des0034	0.859375	1.30469	0.990625	5	47.8906	65.7813	4.92188	0.489063	0.15625	
sobol1_14_des0035	0.884375	1.24219	0.865625	5	38.5156	47.0313	10.5469	0.476563	3.90625	

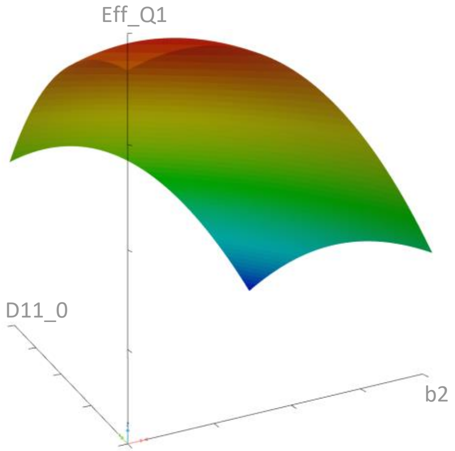
Optimization | Surrogate Models

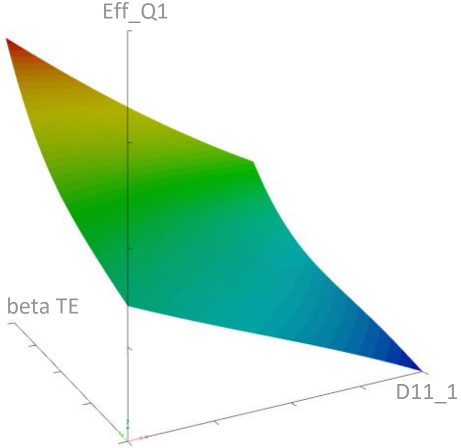
- Surrogate models created in a separate project using imported design result table from DoE
- Based on the feature *RSMtools*
  - 9 separate models for the 9 considered outputs (H, eff, P at 3 flow rates)
  - Generated models are persistently stored in files
  - Checking yielded high CoP values of 0.95 and above



Optimization | Surrogate Models

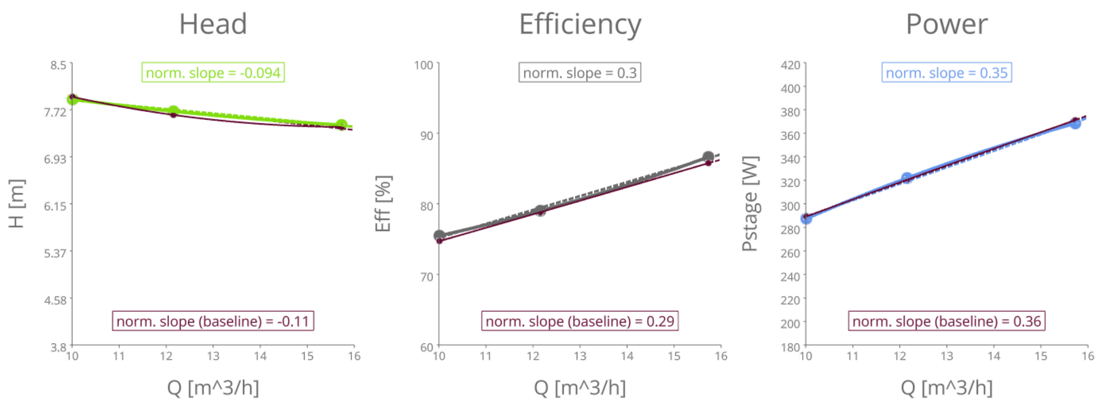
- Surrogate models created in a separate project using imported design result table from DoE
- Based on the feature *RSMtools*
  - 9 separate models for the 9 considered outputs (H, eff, P at 3 flow rates)
  - Generated models are persistently stored in files
  - Checking yielded high CoP values of 0.95 and above
  - Individual response surfaces can be visualized





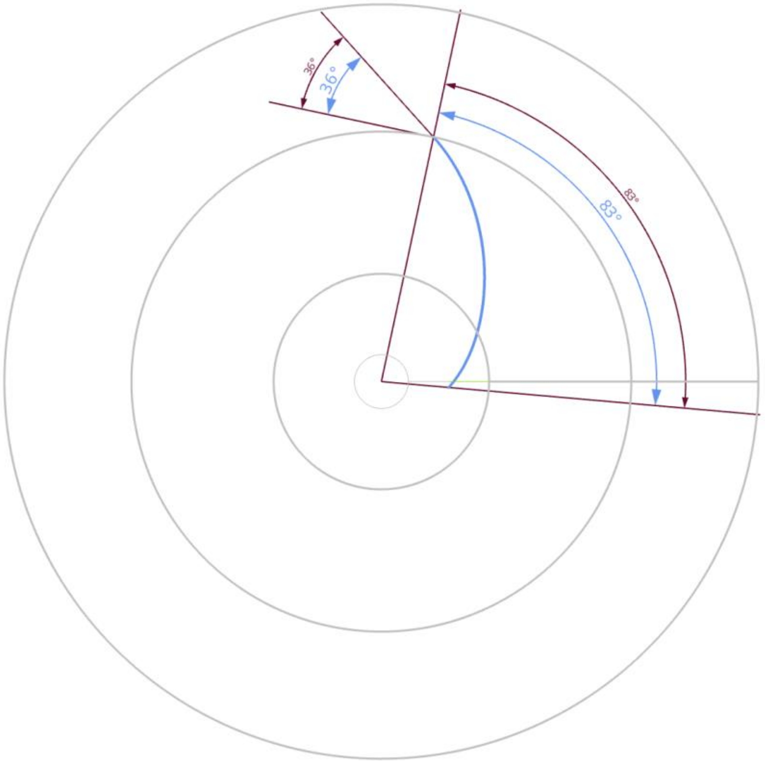
Optimization | Surrogate Models

- The surrogates provide values for the 9 primary output parameters
- The values are plotted in diagrams
- Slopes of the curves (from linear interpolation) are computed as derived values



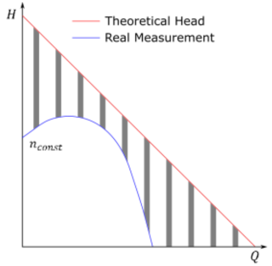
Optimization | Surrogate Models

- The surrogates provide values for the 9 primary output parameters
- The values are plotted in diagrams
- Slopes of the curves (from linear interpolation) are computed as derived values
- A strongly simplified geometry model (with only the hub camber line) provides the TE blade angle and the total wrap angle

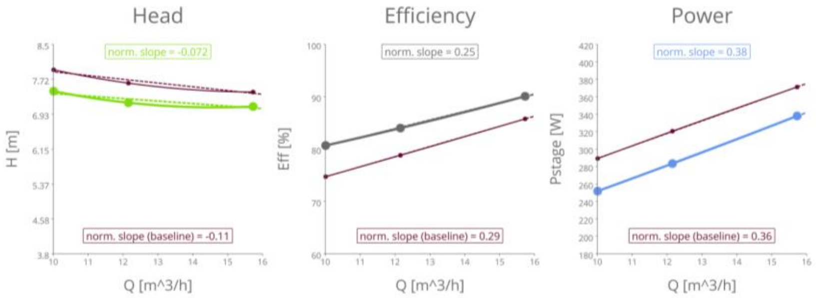


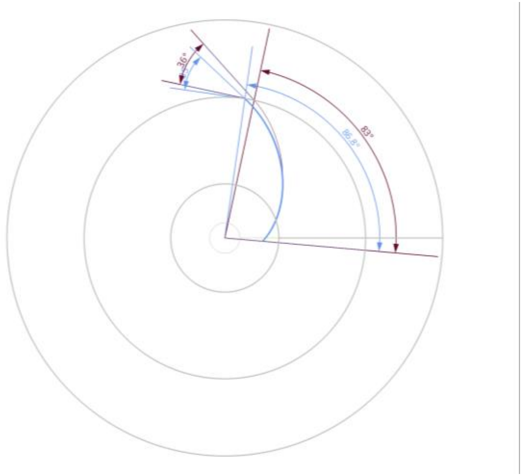
Optimization | Surrogate Models

- Optimizations can now be run on surrogate models
- Final goal is to simply optimize for minimal EEI, but:
  - Calculation of the EEI is done with measured curves
  - Here, pump performance is evaluated by impeller only CFD simulations at fixed rpm
  - Approximation of the measured head curves by application of different assumptions on calculated curve



→ Still work in progress

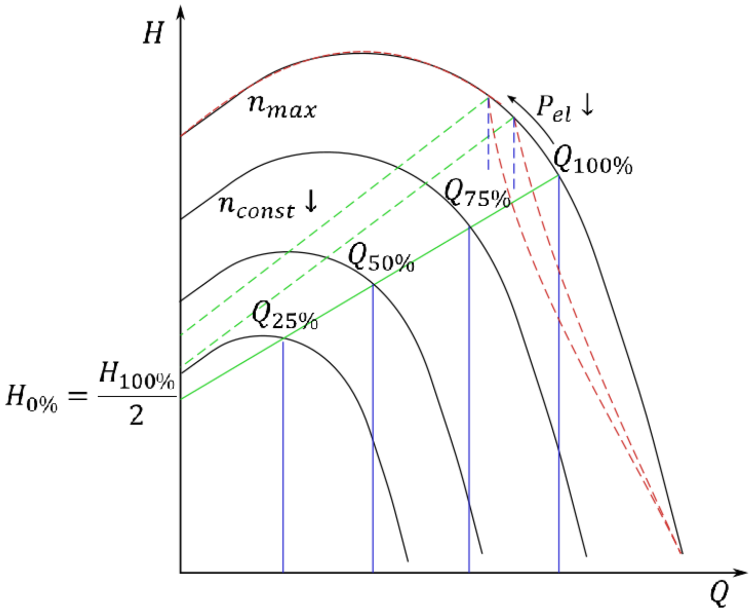




Optimization | Surrogate Models

- Testing of the surrogate model using assumptions:
  - Increase efficiency at lowest flow rate (due to stronger weighting)
  - Reduce slope of power curve (to prevent breakdown of head at higher flow rates and shifting of $Q_{100\%}$ point)

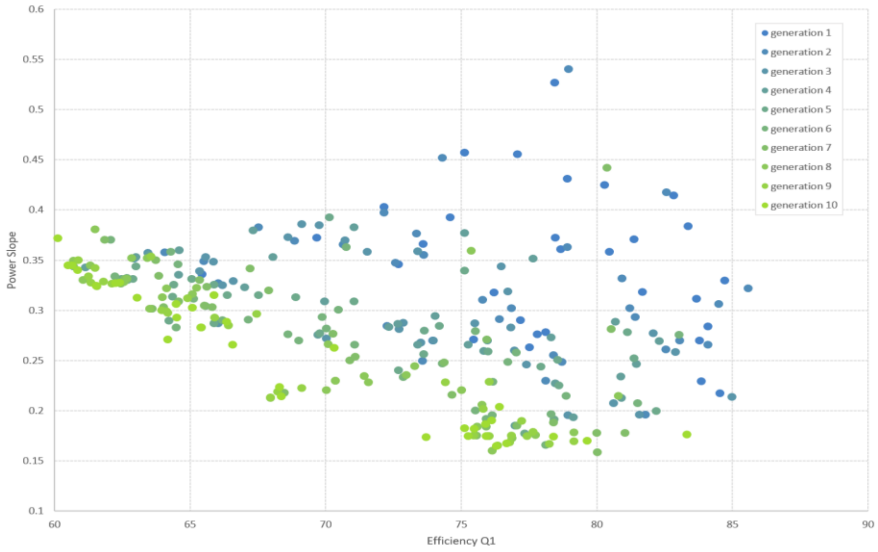
→ Should lead to lower EEI



$$EEI = \frac{0.06 P_{L,100\%} + 0.15 P_{L,75\%} + 0.35 P_{L,50\%} + 0.44 P_{L,25\%}}{P_{ref}} C_{20\%}$$

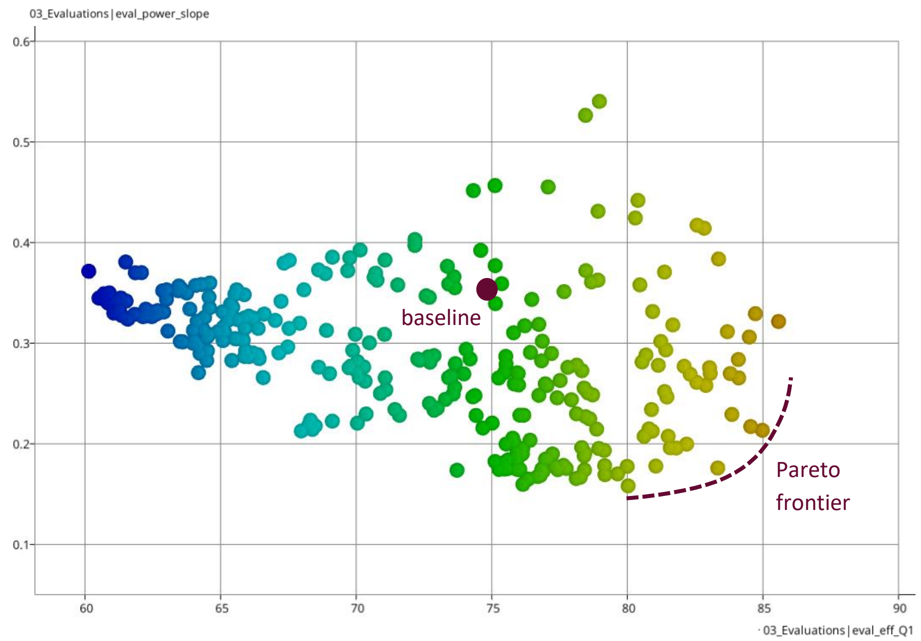
Optimization | Surrogate Models

- NSGA run with 10 generations and 32 design per generation → 320 designs
  - ~30 min runtime (i.e., ~10 designs per minute)



Optimization | Surrogate Models

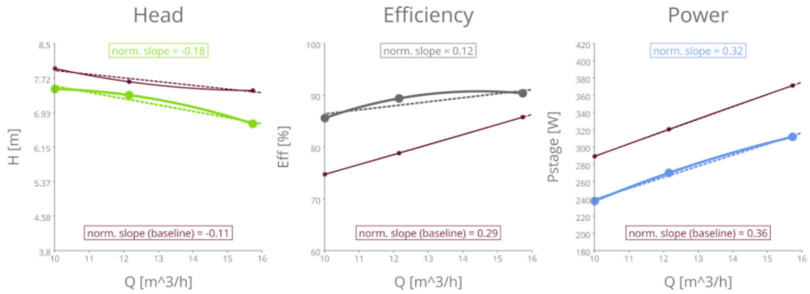
- NSGA run with 10 generations and 32 design per generation → 320 designs
  - ~30 min runtime (i.e., ~10 designs per minute)
  - Several Pareto optimal designs

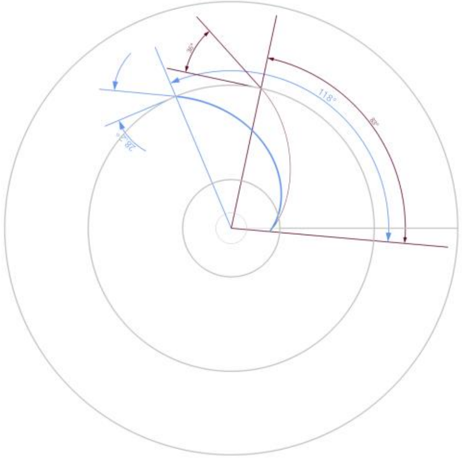


Optimization | Surrogate Models

- NSGA run with 10 generations and 32 design per generation → 320 designs
  - ~30 min runtime (i.e., ~10 designs per minute)
  - Several Pareto optimal designs

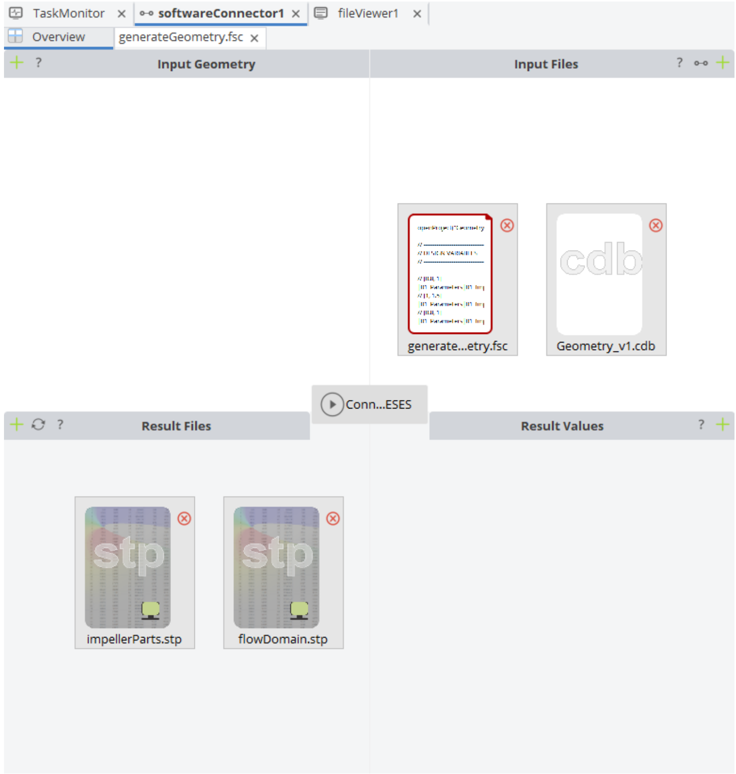
- Selected design
  - Smaller TE blade angle
  - Larger wrap angle
  - 6 blades (baseline: 7)





Optimization | Surrogate Models

- Integrated software connector to launch CAESES in batch mode and generate geometry for selected variant on demand
  - Open parametric model
  - Send design variable values via FSC script
  - Save project file
  - Export meridional contours, blade, and flow domain



Conclusions

- Using SimScale CFD analysis in the cloud allows for high degree of parallelization and rapid evaluation of a large number of impeller variants at multiple operating points
- Surrogate models provide a persistent storage for the generated database and can efficiently predict performance with a satisfactory degree of precision
- A quick optimization of the impeller geometry can be carried out using the surrogate models and custom requirements
- With these components, a first iteration of the hydraulic part of the toolchain for the minimization of the pump's EEI could be realized

Acknowledgements

- Thank you to all people who contributed to the project, especially:
  - Toni Klemm, KSB
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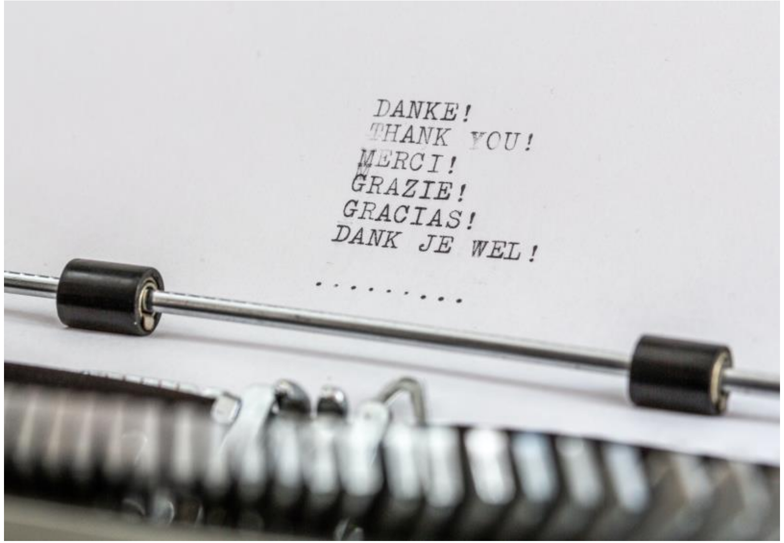
  - Johannes Weber, FRIENDSHIP SYSTEMS



Thank you for your attention!

brenner@friendship-systems.com
www.CAESES.com

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