Automated Design Optimization: Case Study of Impeller Blade Geometry

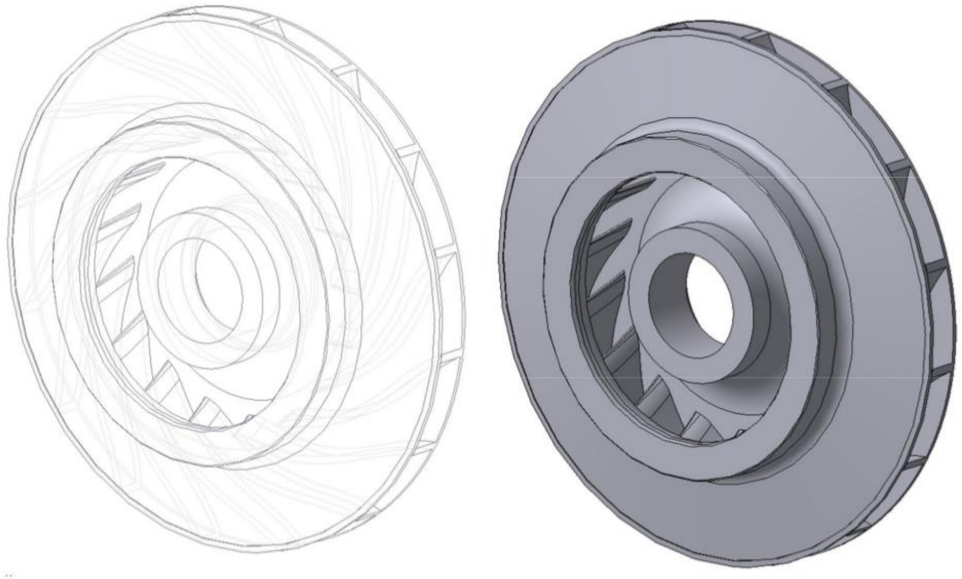
Anton Saratov, DATADVANCE

Impeller blade geometry optimization

Use case demonstrates the implementation of blade parameterization for impeller performance optimization study

We consider a small centrifugal air pump with fixed operating regime. Only the geometry of impeller blade can be changed.

Goal is to determine the geometry for maximal efficiency while preserving outlet pressure value:



- 3D simulation with significant computation time.
- Number of simulations should be as small as possible.
- Effective parameterization is a key.

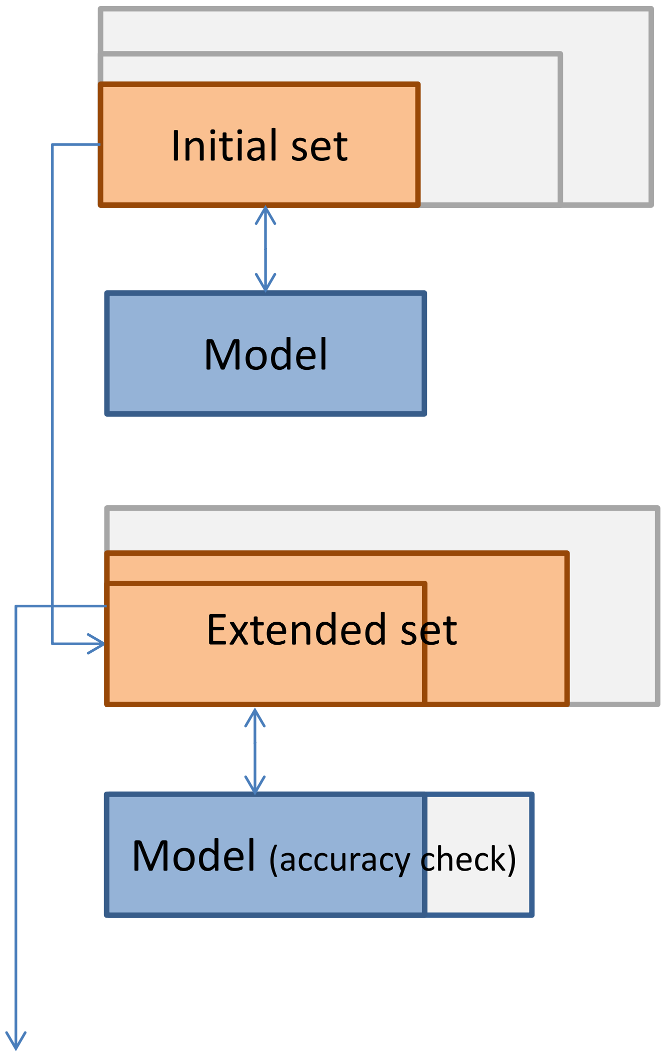
Effective parameterization problem

Common problems for complex geometry parameterization:

- Excessive (by points) and poor parameters set.
- Unclear influence of parameters on performance.
- Box ranges lead to significant number of meaningless configurations.
- Box ranges in parameter space do not cover response space well.

Implementation of multi-scale methodology in optimization:

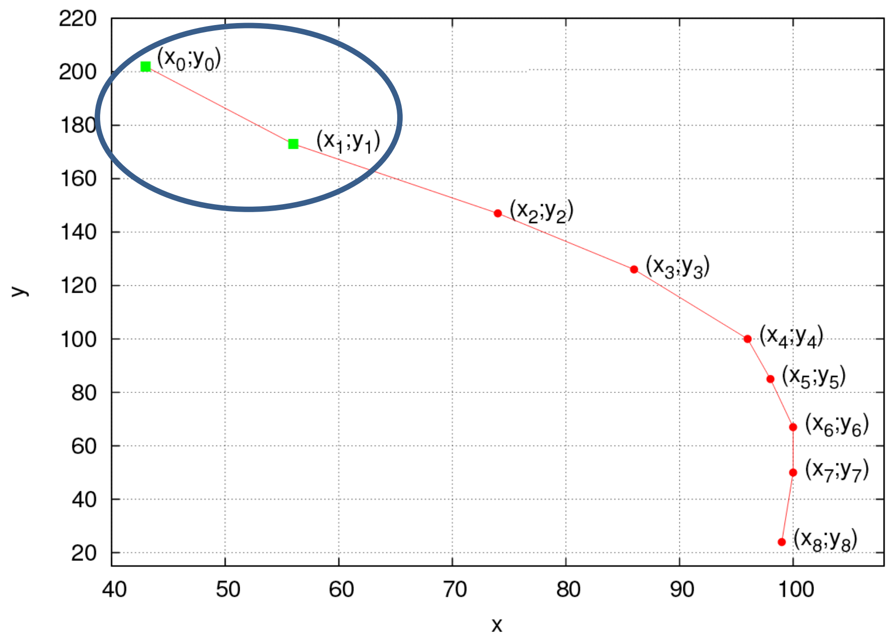
- Reveal and use only a few most relevant parameters at first stage.
- Fix them or narrow the range.
- Extend parameterization with next-order accuracy parameters.
- Check the correspondence between parameterization and model accuracies.



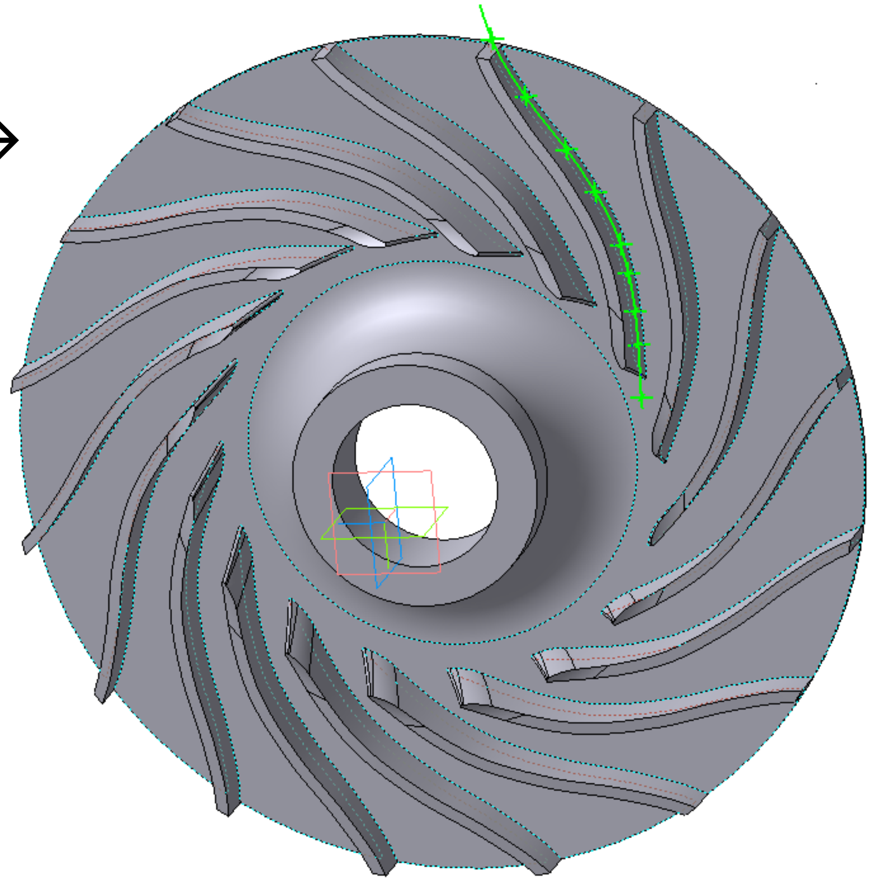
Implementation for impeller: simplification

Camber line is defined with 7 active points → **14 parameters**.
Reparameterization is needed for effective optimization.

Width of blade is assumed to be small and essentially constant → **only camber line profiling is considered**.



First two points positions are fixed

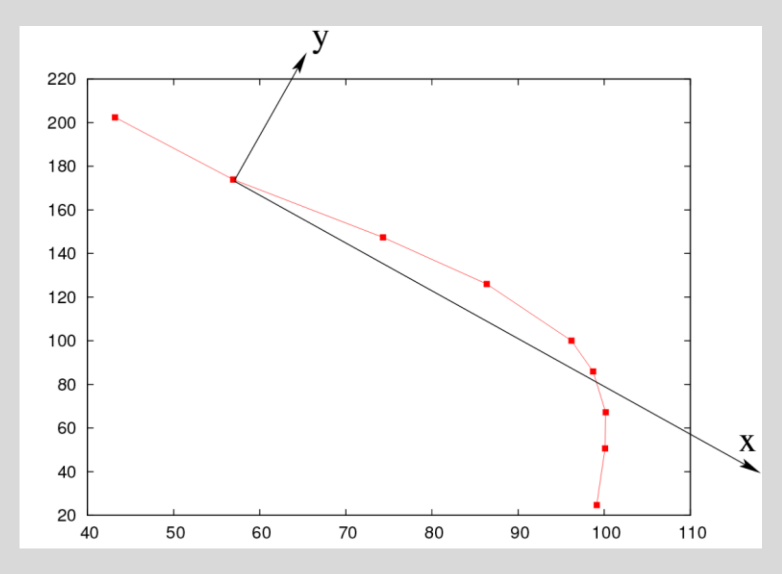


Parameterization development basics

Most relevant parameters:

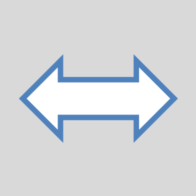
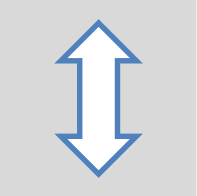
1. Inlet and outlet skeleton angles.
2. Blade curvature distribution along camber line.

Inlet angle is fixed by particular problem definition → natural introduction of **local coordinate system**.

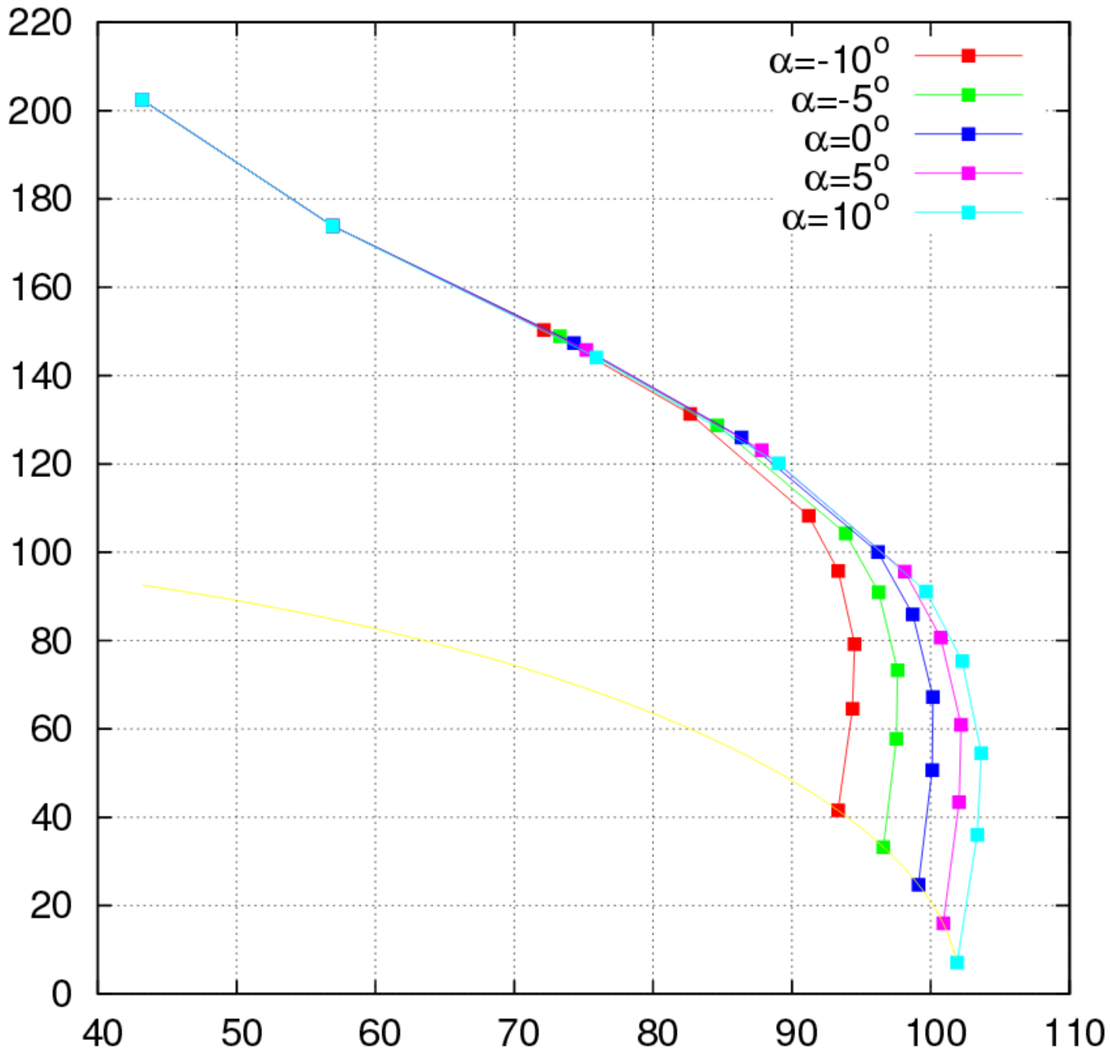


Outlet angle and curvature profile can be controlled by:

- Rotation of this frame
- Position of the camber line maximum
- Height scaling

Local frame rotation



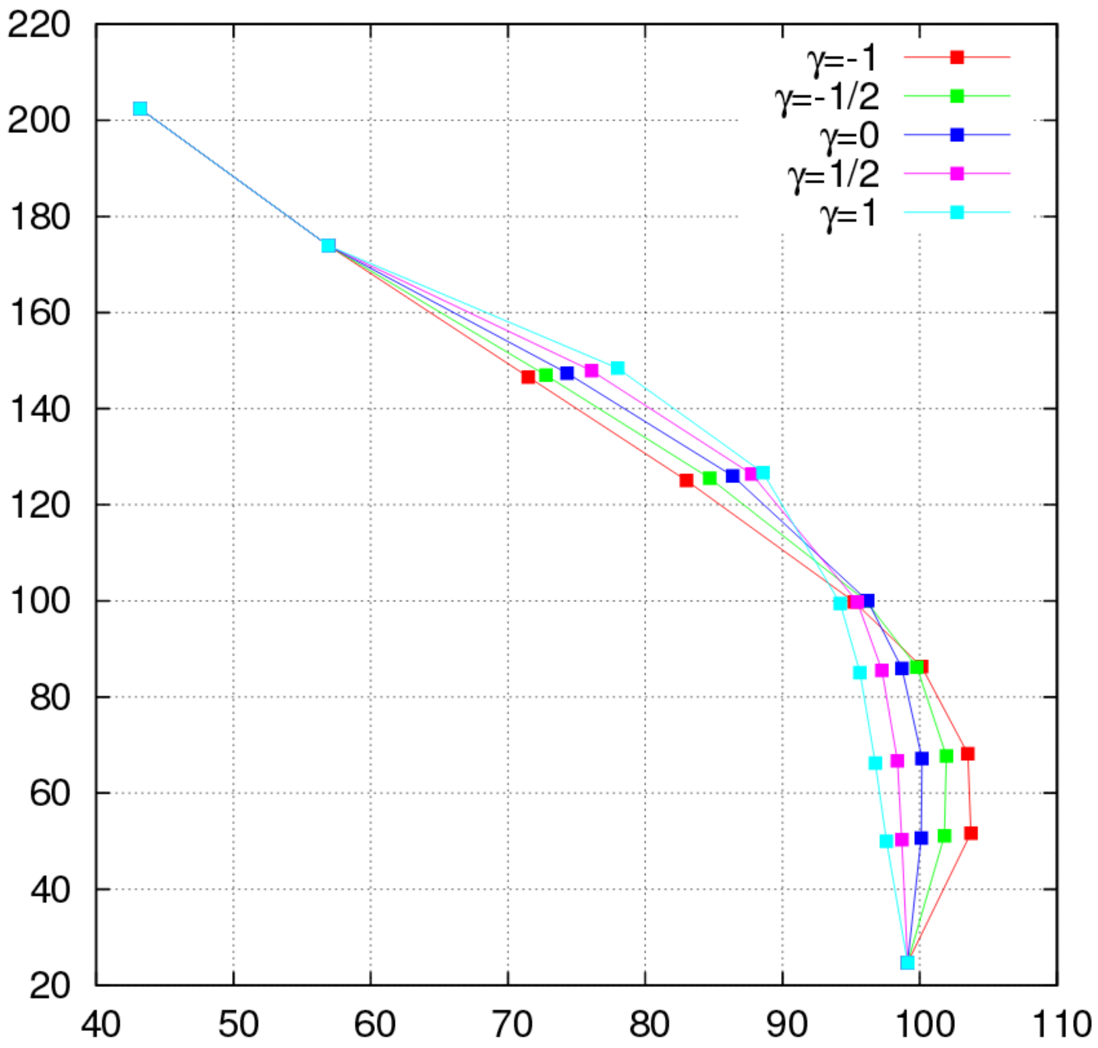
Rotation angle – prime degree of freedom.
It directly changes the outlet skeleton angle.

However, this transformation leads to outlet edge shift → correction needed.

Imposed correction procedure:

Upon rotation, camber line is scaled in x direction to provide the same distance from impeller origin.

Camber line maximum position

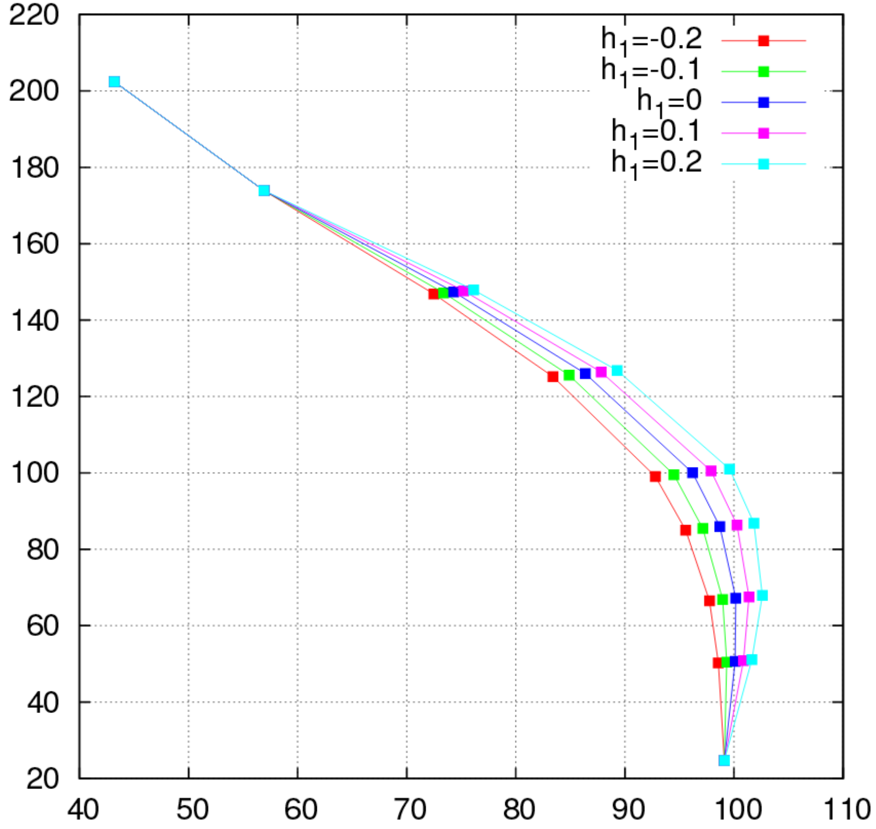


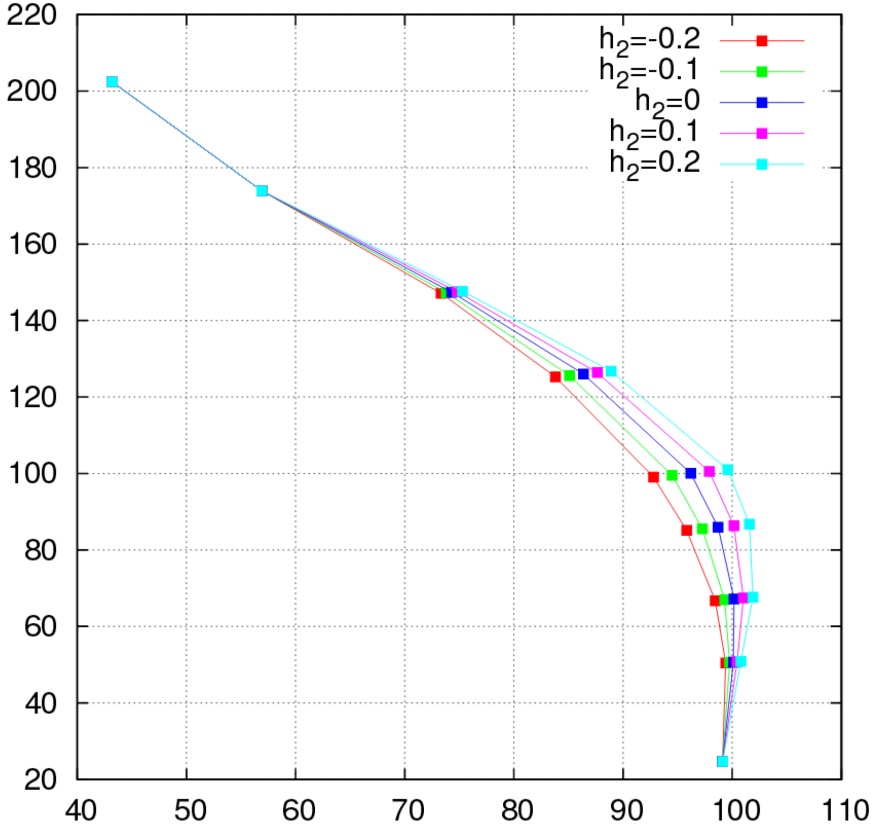
One dimensionless parameter for smooth deformation of the curve.

Shifts the position of maximum in local frame closer to inlet or outlet region.

Typical range for physically meaningful profiles [-1;1]

Camber line height control





Scaling law for curve height in local frame: **Height = Initial Height * (h1 + h2 *y)**

Higher-order terms are not considered due to “equal accuracy influence” reasons.

Simulation model overview

Parameterization → CAD → ANSYS Workbench (CFX)

Number of blades: 16
Ideal gas, specific heat ratio 1.4
Rotation velocity 10 000 RPM

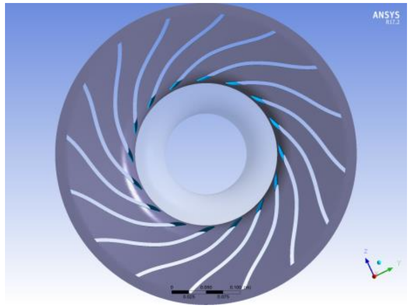
Boundaries:

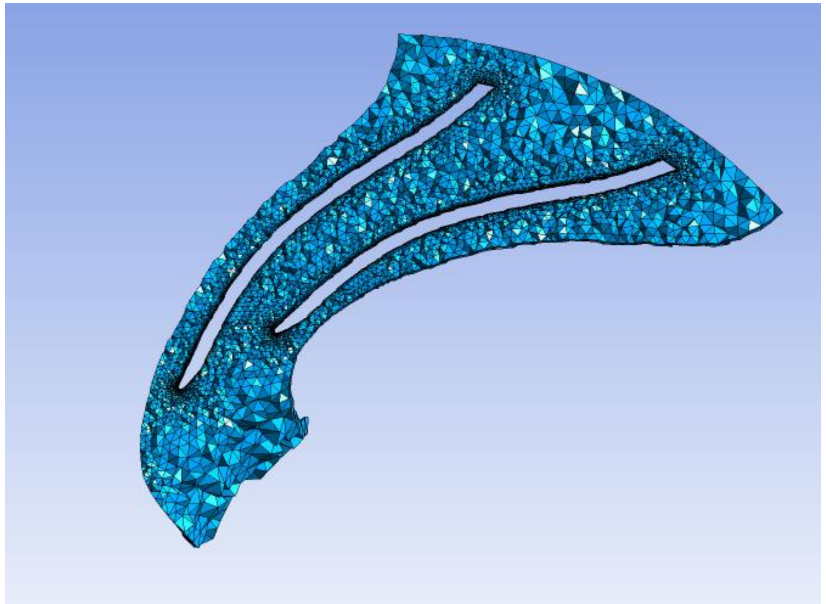
- static pressure 0.1 MPa
- mass flow 0.1 kg/sec

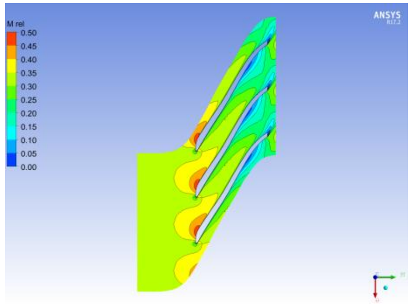
Mesh size ~ 250 000 cells

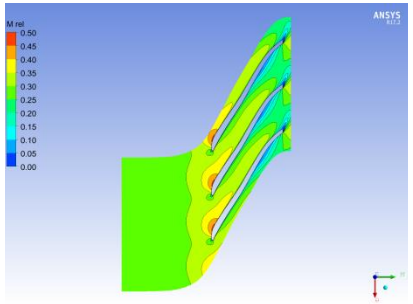
Outputs:

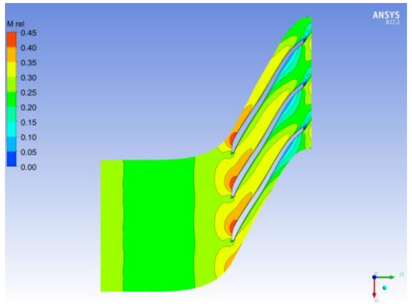
- polytropic efficiency $\eta = \frac{k-1}{k}\frac{\ln \epsilon}{\ln \tau}$
- pressure







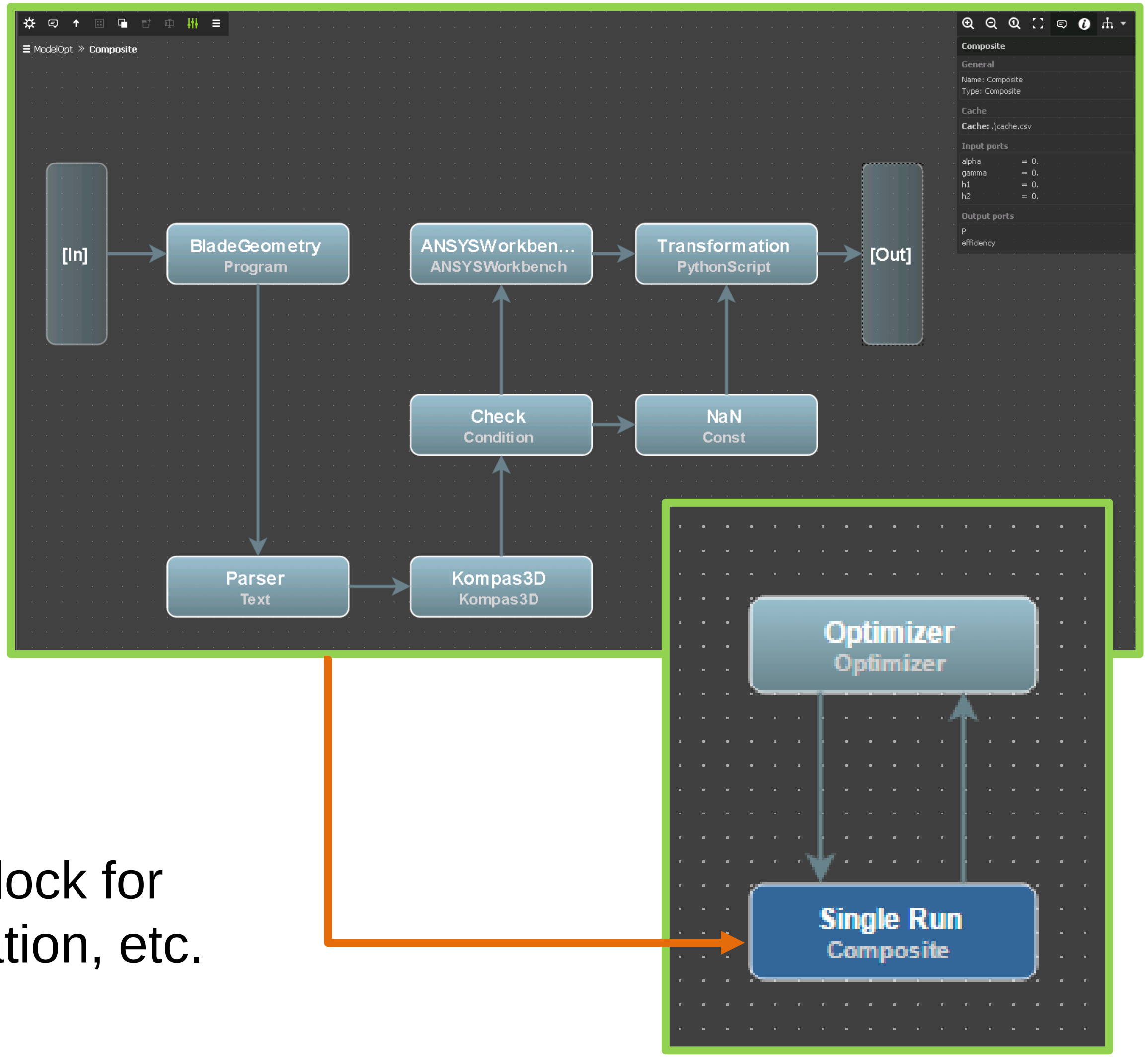




Simulation automation

Simulation workflow was created in **pSeven** platform:

- Geometry parameterization is implemented as a block with custom Python script.
- CAD system is integrated via direct integration block.
- Simulation in ANSYS Workbench is also controlled by direct integration block.
- Workflow performs extended rebuild error control.



This workflow can be further used as a composite block for different studies: DoE, Sensitivity analysis, Optimization, etc.

Optimization problem statement

Parameters:

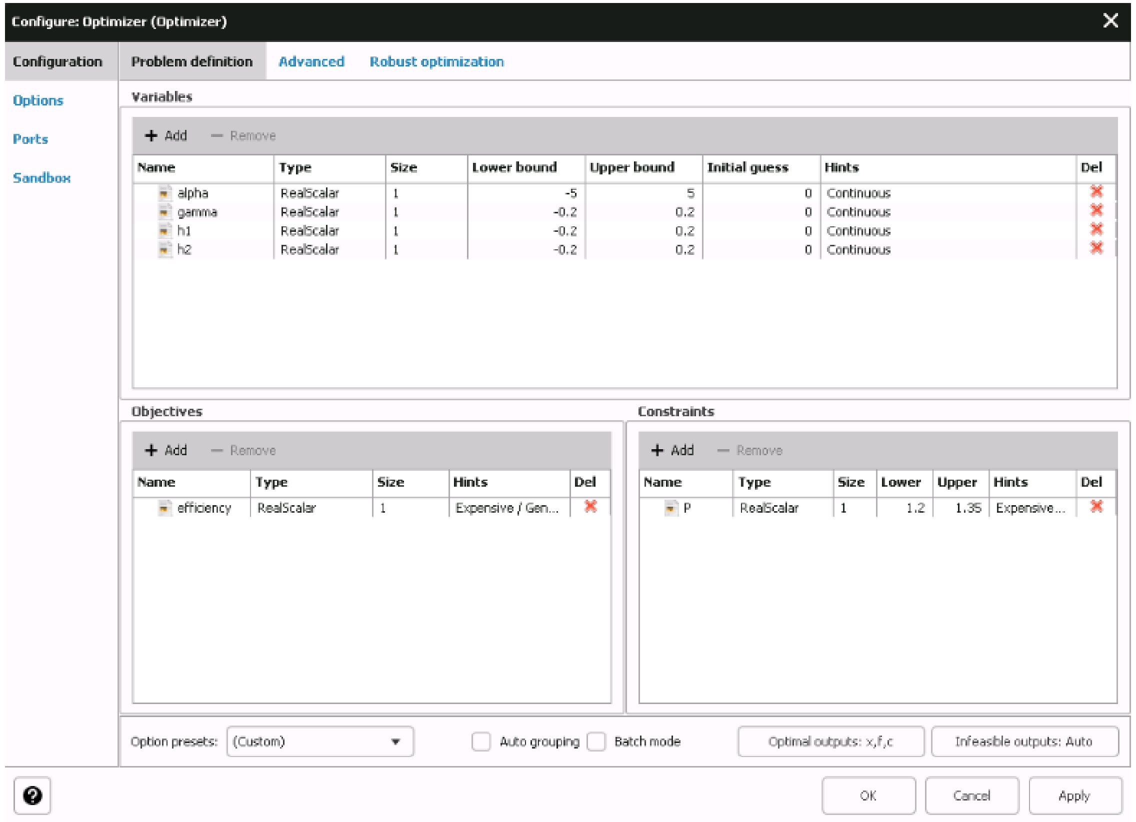
Name	Description	Lower bound	Upper bound
α	Rotation angle, deg.	-5	5
γ	Maximum position	-0.2	0.2
h1	Const. scaling coef.	-0.2	0.2
h2	Linear scaling coef.	-0.2	0.2

Goal:

Name	Description	Type*	Goal
η	Polytropic efficiency	Expensive	maximum

Constraint:

Name	Description	Type*	Bounds
P	Pressure, MPa	Expensive	[0.12; 0.135]

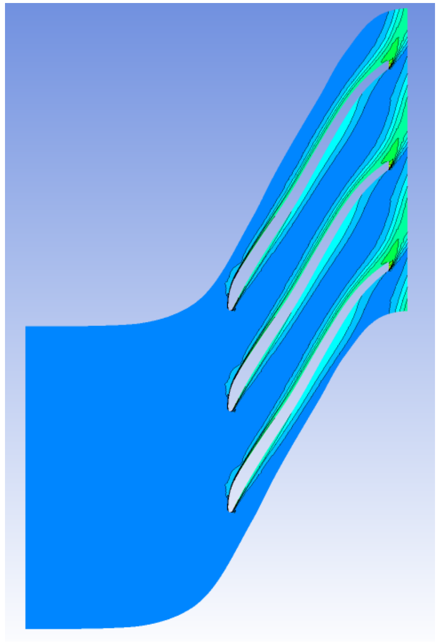
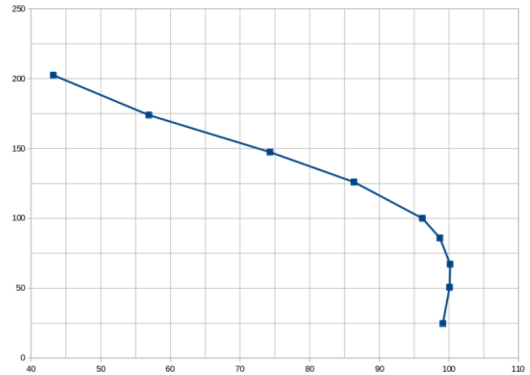


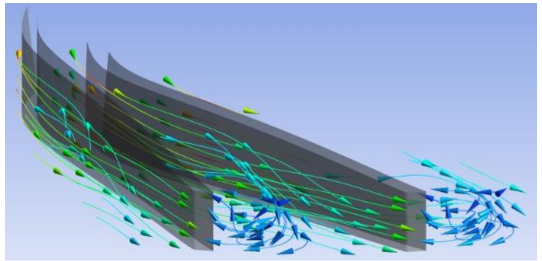
* In terms of computational cost. “Expensive” hint turns on the Surrogate-Based Optimization class of algorithms.

Optimization results

SBO algorithm was used for optimization.
Total simulation budget 56 points.
Overall time ~19 hours.

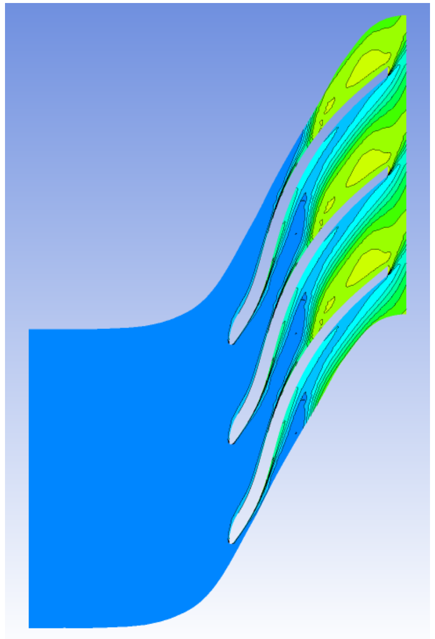
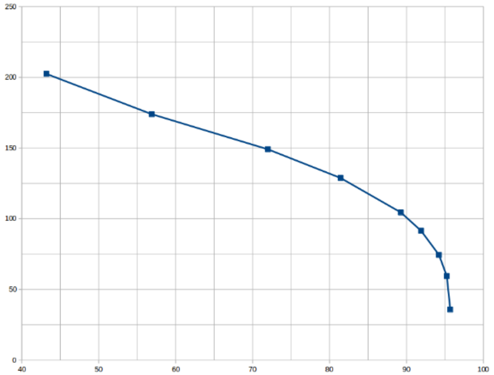
Polytropic efficiency increased: 94.6% → 95.3%
Operating conditions (pressure) change is negligible.

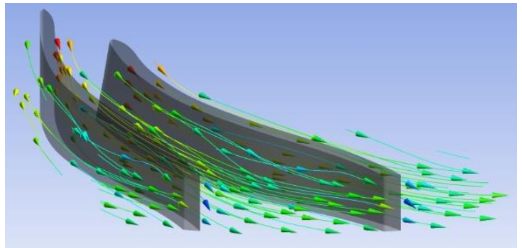





SBO algorithm in pSeven:

- Auto or manual globalization control
- GP based
- NaN support
- Stable to numerical noise
- Explicit budget option



Conclusions

- Effective parameterization of impeller blade geometry introduced
- Only 4 parameters allow to create a variety of meaningful profiles
- Parameterization can be naturally extended to meet accuracy demands
- Automated workflow created to implement the approach
- Optimization problem solved with significant efficiency improvement

Parameterization extension

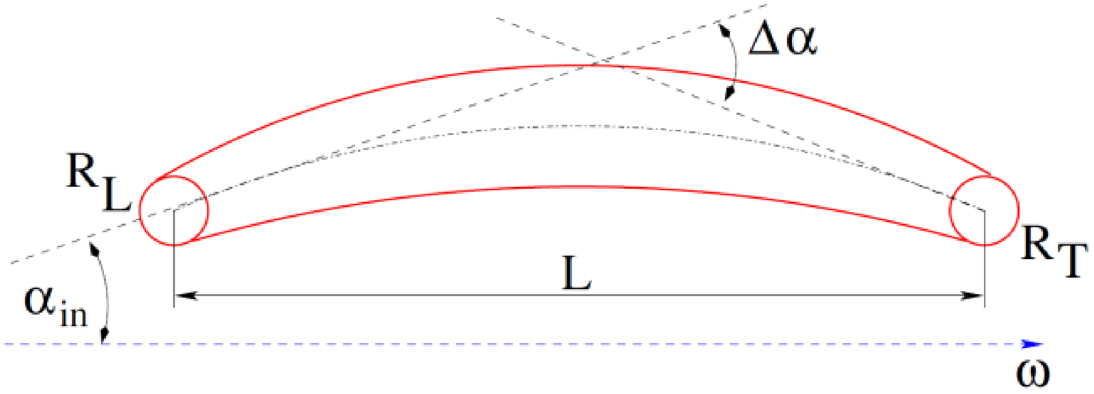
This approach can be implemented in a variety of similar optimization problems of:

- Radial pumps
- Gas turbines
- Steam turbines
- etc.

Parameterization extension: turbine blade

2D profile parameters:

- inlet skeleton angle α
- deflection angle ($\Delta\alpha$)
- inlet radius *RL*
- outlet radius *RT*,
- chord length *L*
- profile controls



Variation along blade for different stages:

First order angles dependencies:

$$\alpha(h) = \alpha 0 + \alpha 1 h$$
$$\Delta\alpha(h) = \Delta\alpha 0 + \Delta\alpha 1 h$$

Second order angles dependencies:

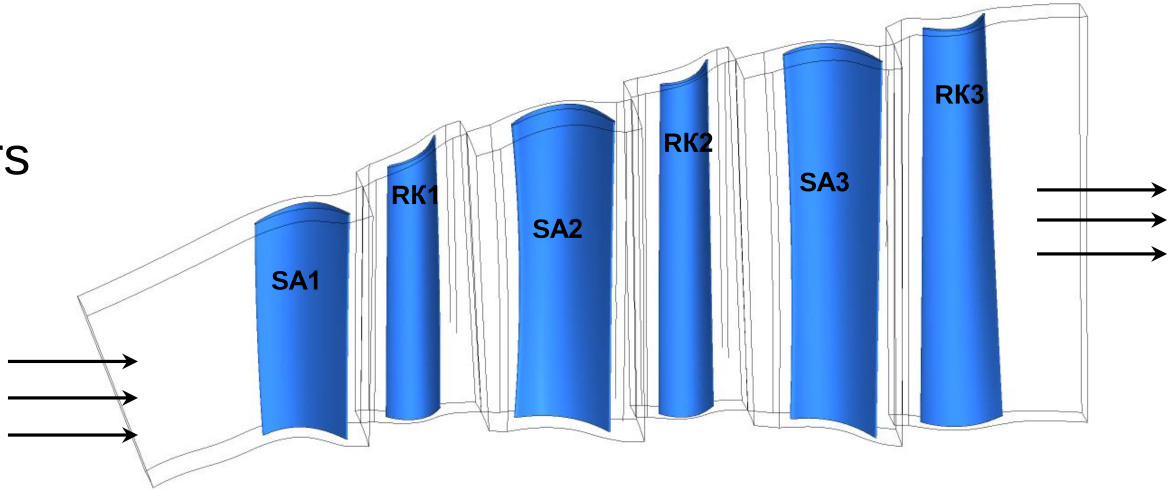
$$\alpha(h) = \alpha 0 + \alpha 1 h + \alpha 2 h^2,$$
$$\Delta\alpha(h) = \Delta\alpha 0 + \Delta\alpha 1 h + \Delta\alpha 2 h^2$$

Total number of parameters: **34**

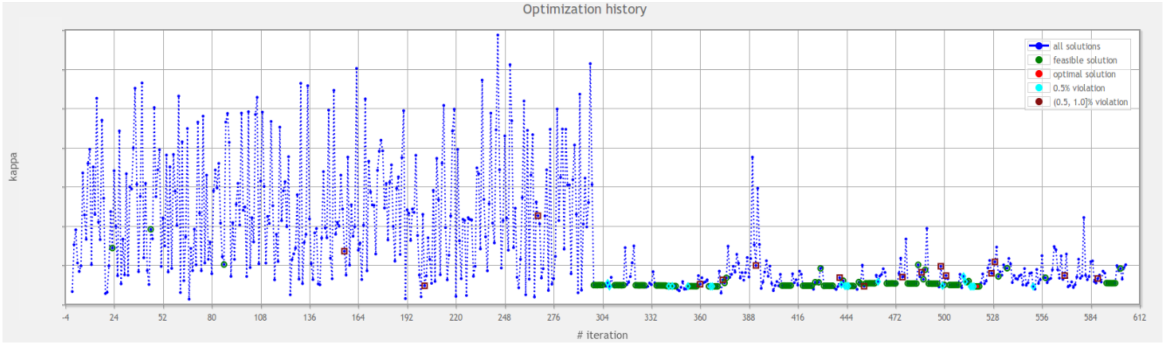
(number of parameters for Bezier curves: 54)

Parameterization extension: turbine blade

- Sectorial simulation model in ANSYS CFX
- Simulation time for one configuration 3,5 hours
- Parallel optimization (10 points each time)
- SBO algorithm, 1 goal, 3 constrains
- Total budget 600 points



- ✓ **Efficiency increase by 0.6%**
- ✓ Mass flow constraint satisfied
- ✓ Geometry constraints satisfied



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Contacts:

DATADVANCE SAS
42 Avenue du Général de Croutte
31100, Toulouse
France
Tel.: +33 (0) 5 82-95-59-68

DATADVANCE LLC
Nauchny proezd 17
117246, Moscow
Russia
Tel.: +7 495 669-68-15

info@datadvance.net
www.datadvance.net