Automated Multidisciplinary Optimization of a Transonic Axial Compressor (AIAA-2009-0863)

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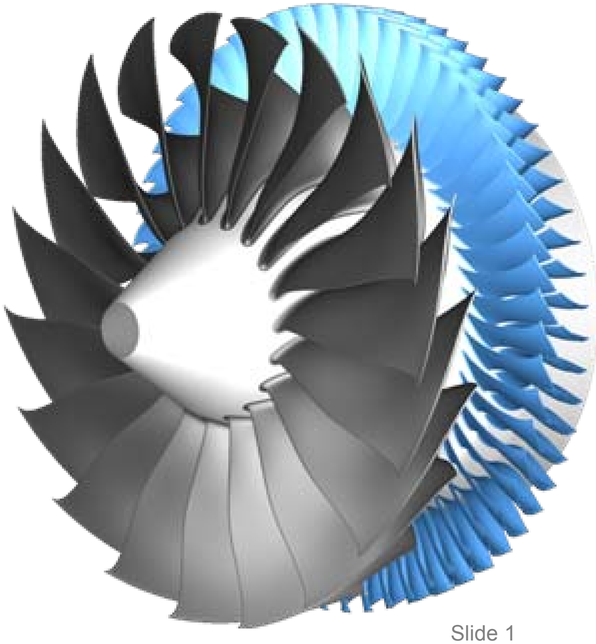
Ulrich Siller, Christian Voß, Eberhard Nicke

German Aerospace Center (DLR)
Institute of Propulsion Technology
Fan and Compressor Department
Cologne, Germany
ulrich.siller@dlr.de



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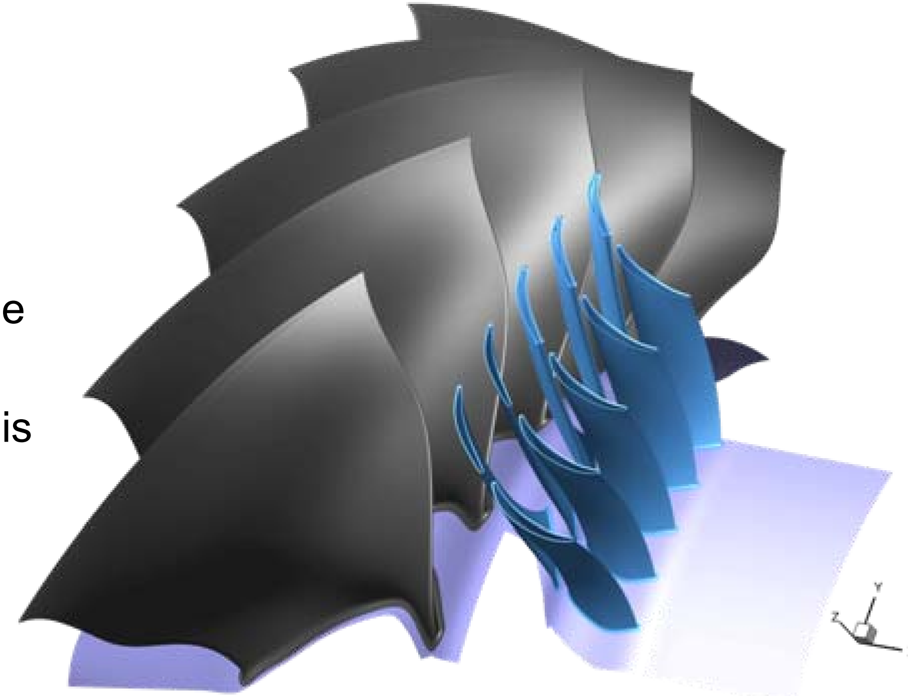
Challenge

- Automatic optimization of a highly loaded, transonic fan in the essential performance map attributes
  - Total pressure ratio,
  - Efficiency,
  - Mass flow rates,
  - Stall margin
  - Stage exit Mach number and swirl angle

  and ensure sustainable mechanical stresses

  in the rotor blade from a finite element analysis



- Starting Point:
  - Rotor: Already high performance due

    to previous 3D-optimizations

    (much lower number of free design parameters and unfeasible mechanical results due to not considering rotor mechanics)

  - Stator: Tandem-stator has been designed with a profile section optimization based on the Euler-BL-Code „Mises“ and a few 3D iterations.

    Before, a single row stator was limiting the stage pressure ratio.

Outline

- Compressor attributes and qualities prior to optimization

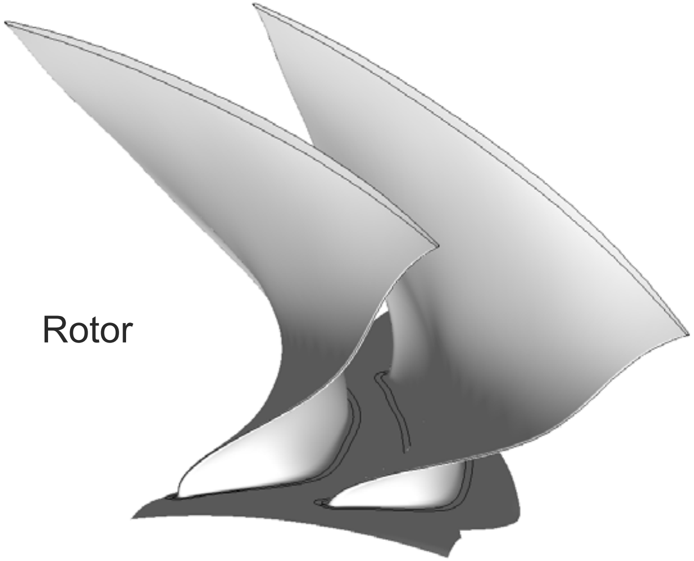
- Optimization setup
  - Numerical setup
  - Free Parameters
  - DLR’s Optimizer “AutoOpti”
  - Objectives and Constraints

- Results
  - Pareto front
  - Geometries
  - Aerodynamics

Design Specification

- Transonic rotor and stator I
- High aerodynamic loading

➔ Bladings with low aspect ratio and high solidity



Rotor

Rotor:

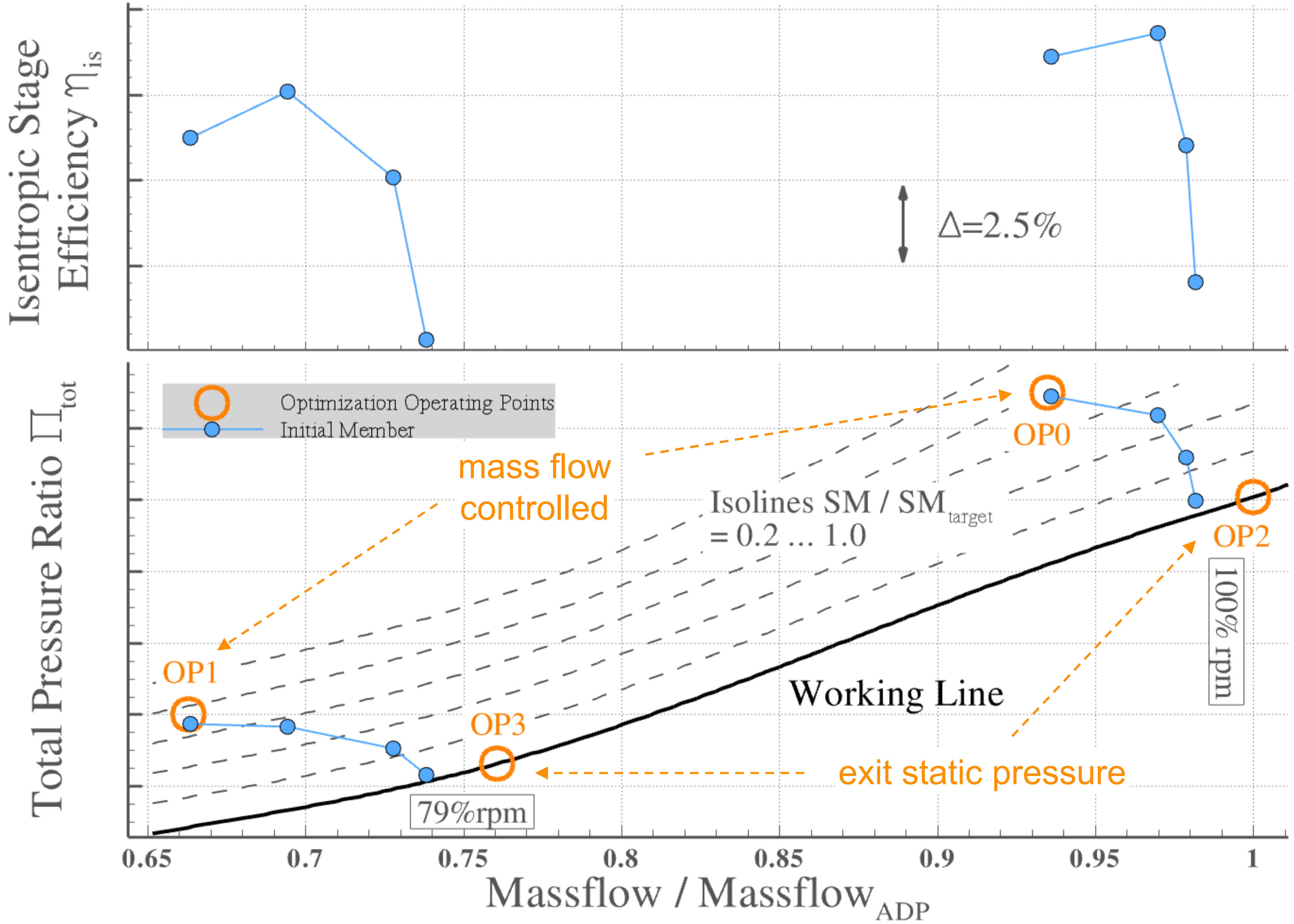
Number of blades	19
Rel. inlet Mach number @ blade tip	1.6
Work coefficient: $cp*\Delta T_{tot}/(0.5*U_{tip}^{2})$	1.02
Specific flow at leading edge	190 kg/(s·m^2)
Inlet radius ratio r_{Hub}/r_{Tip}	0.32

Tandem-Stator

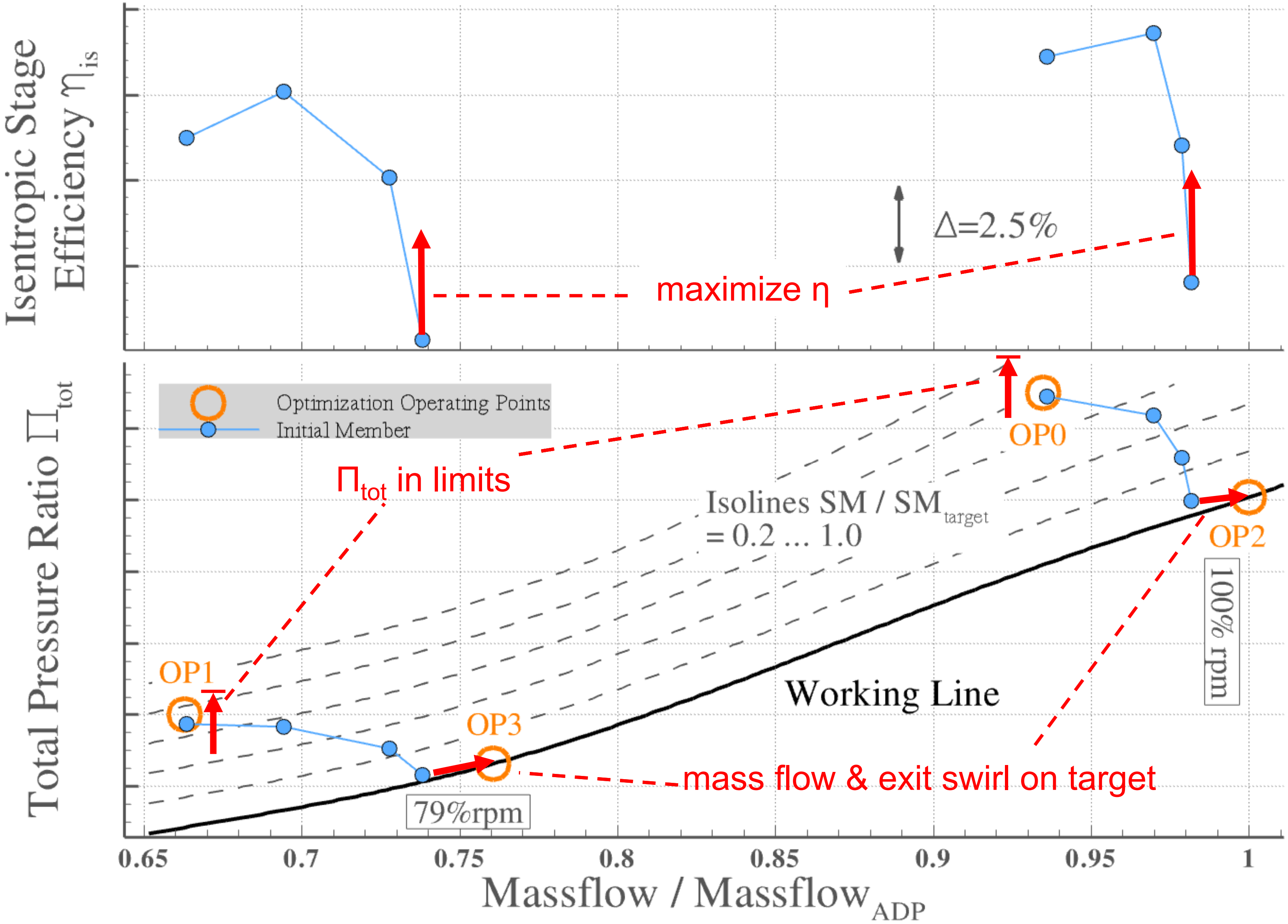
Tandem-Stator:

Number of blades	57
Inlet Mach number @ stator I hub	1.2

Initial Member Performance Map and Operating Points



Optimization Goals



Outline

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  - Performance Map
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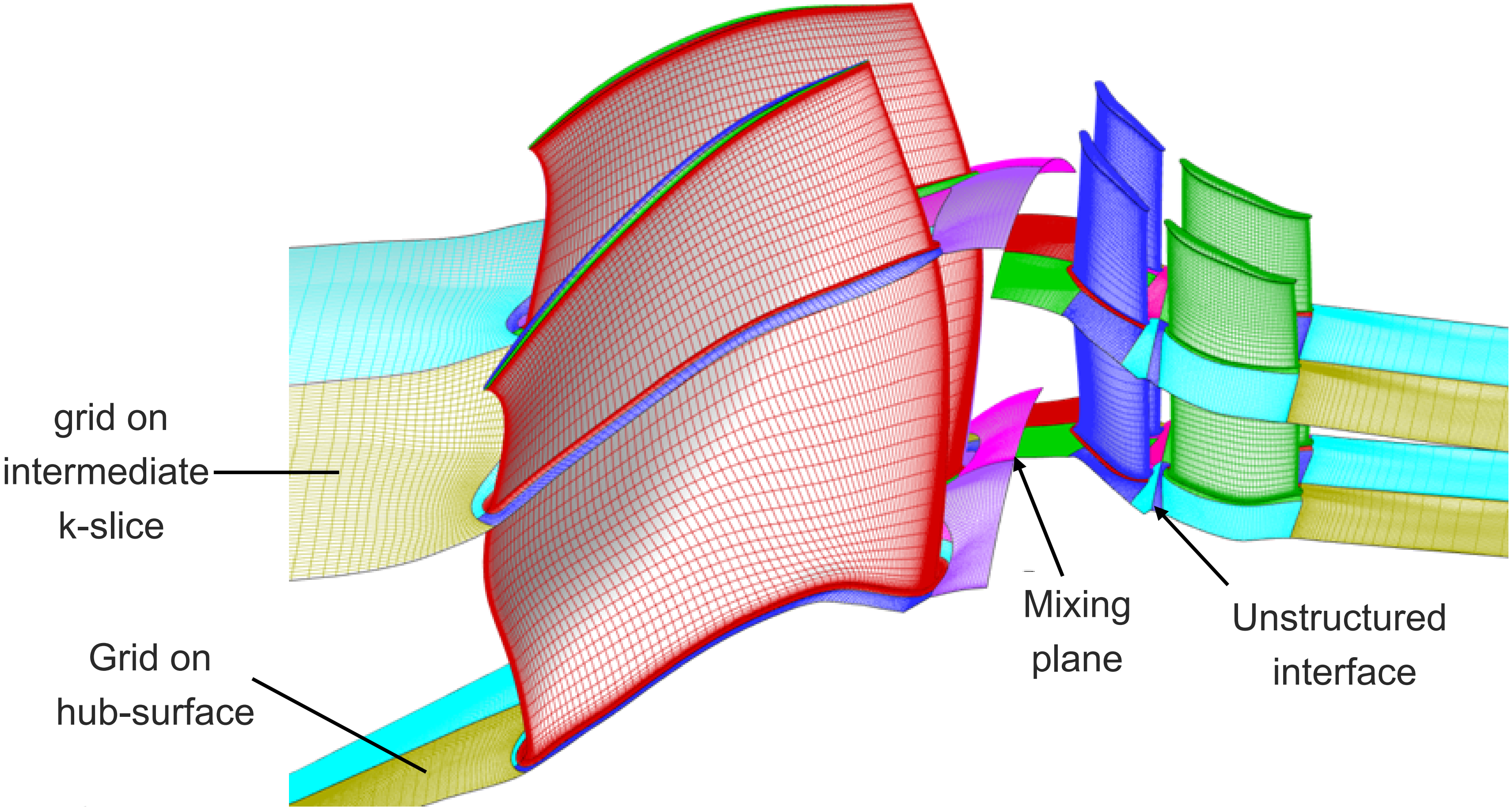
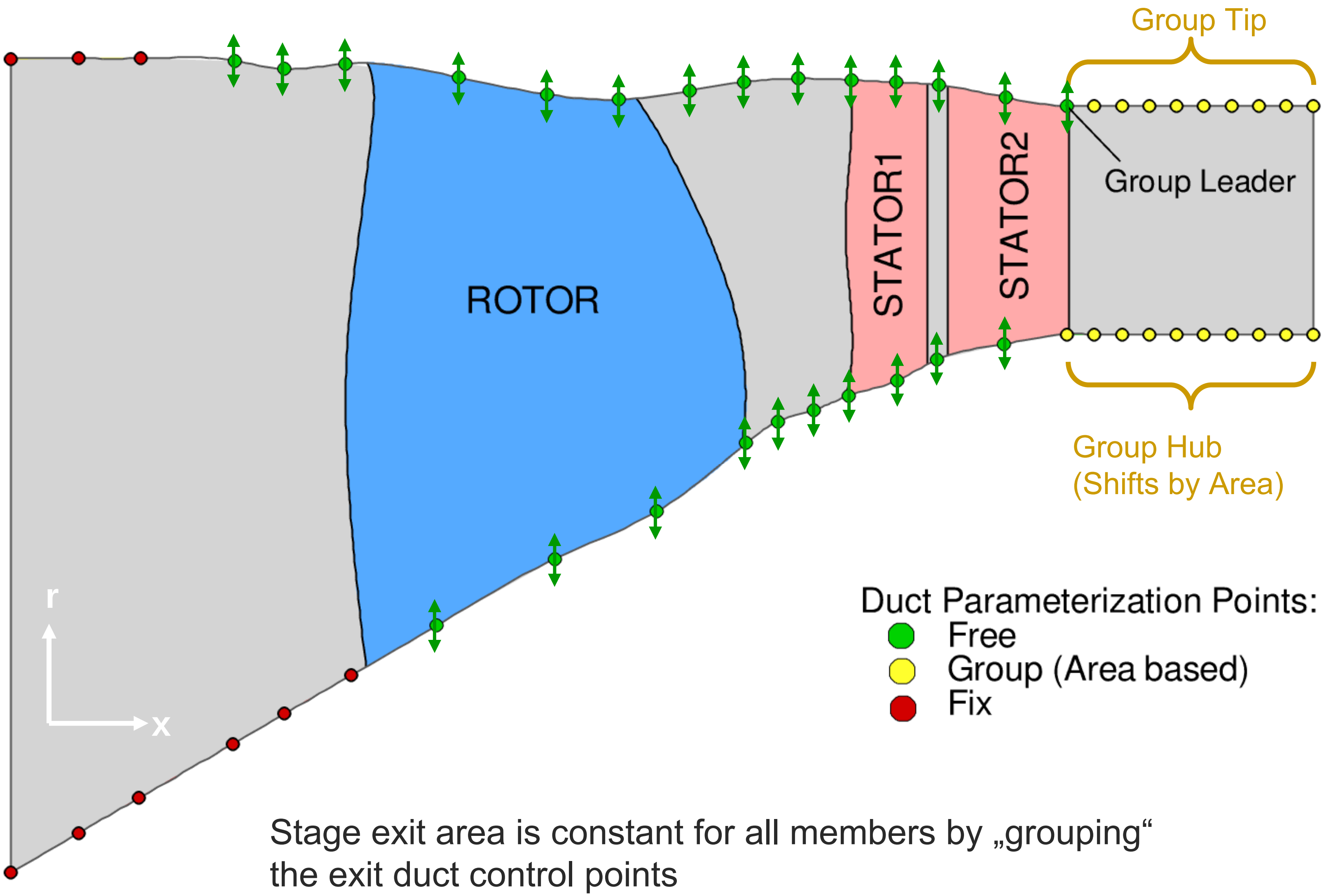
Numerical Setup

- 65 Points in radial direction (13 points in rotor tip clearance)
- Overall 1.3 million grid points for the stage
- 3D-Navier-Stokes solver TRACE (DLR) with Wilcox k-ω turbulence model



Duct Parameterization / Free Parameters

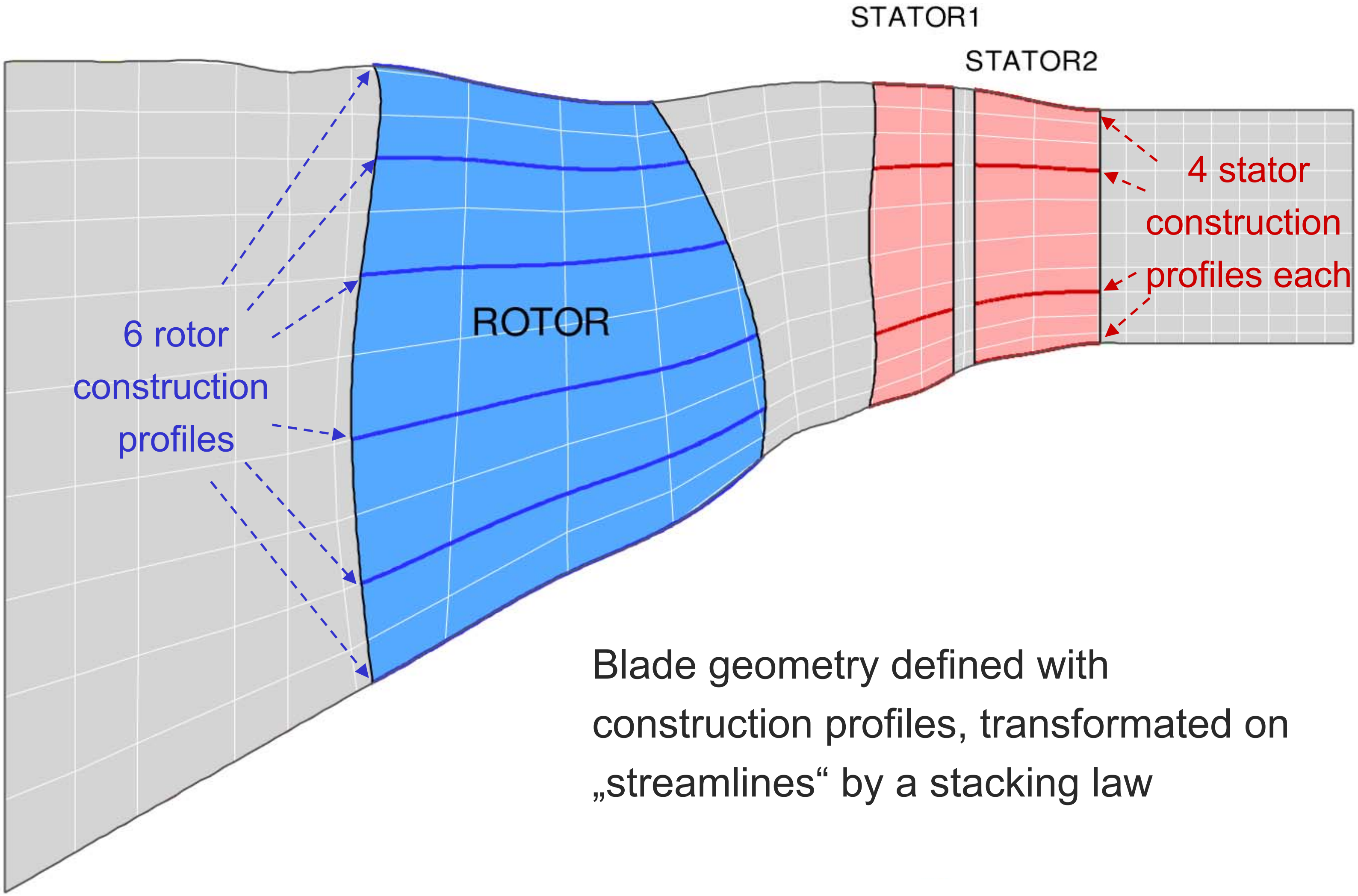


Duct Parameterization Points:

- 🟢 Free
- 🟡 Group (Area based)
- 🔴 Fix

Stage exit area is constant for all members by „grouping“ the exit duct control points

Blade Generation with Construction Profiles

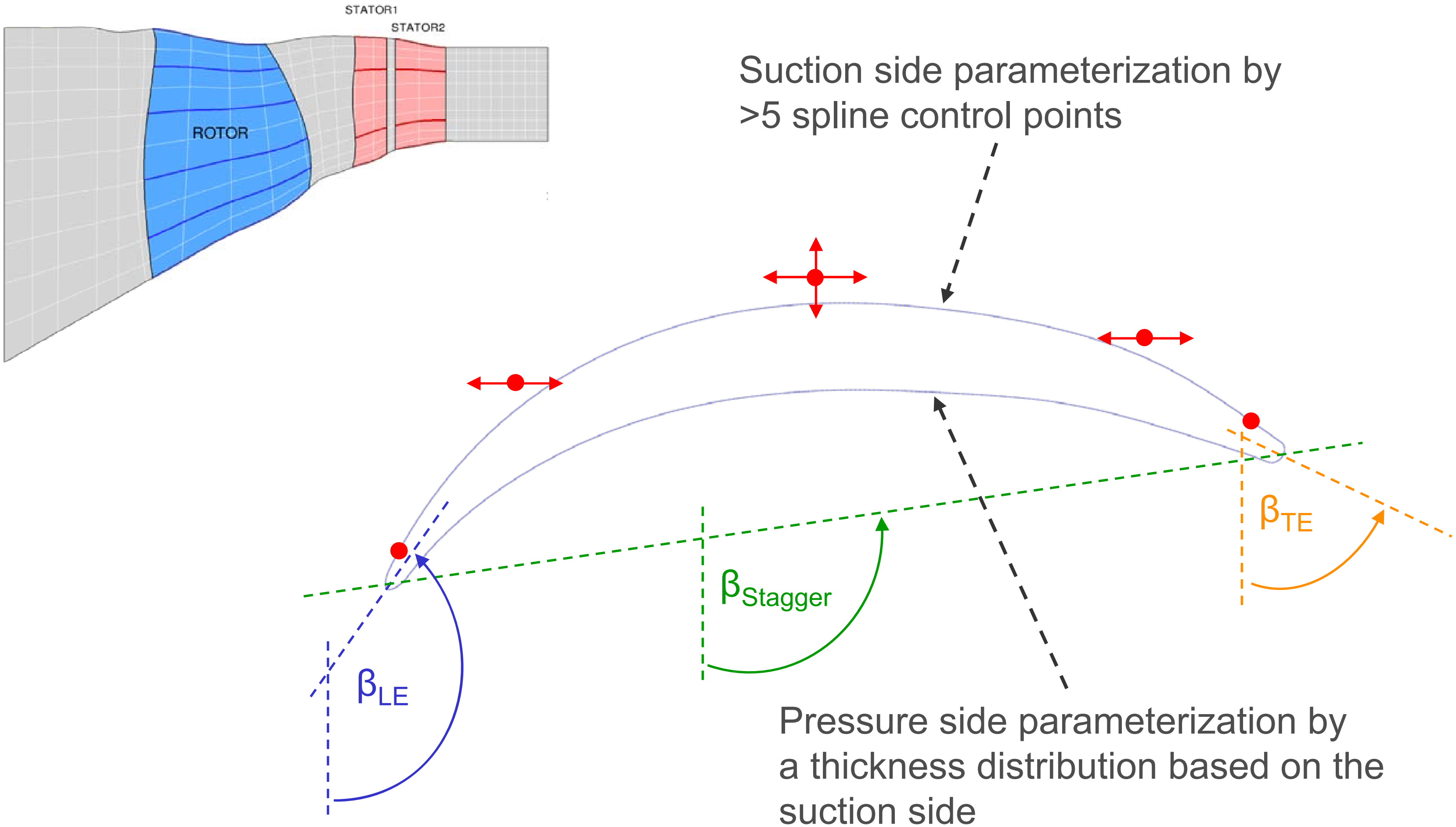


6 rotor construction profiles

4 stator construction profiles each

Blade geometry defined with construction profiles, transformated on „streamlines“ by a stacking law

Profile Parameterization



Suction side parameterization by
>5 spline control points

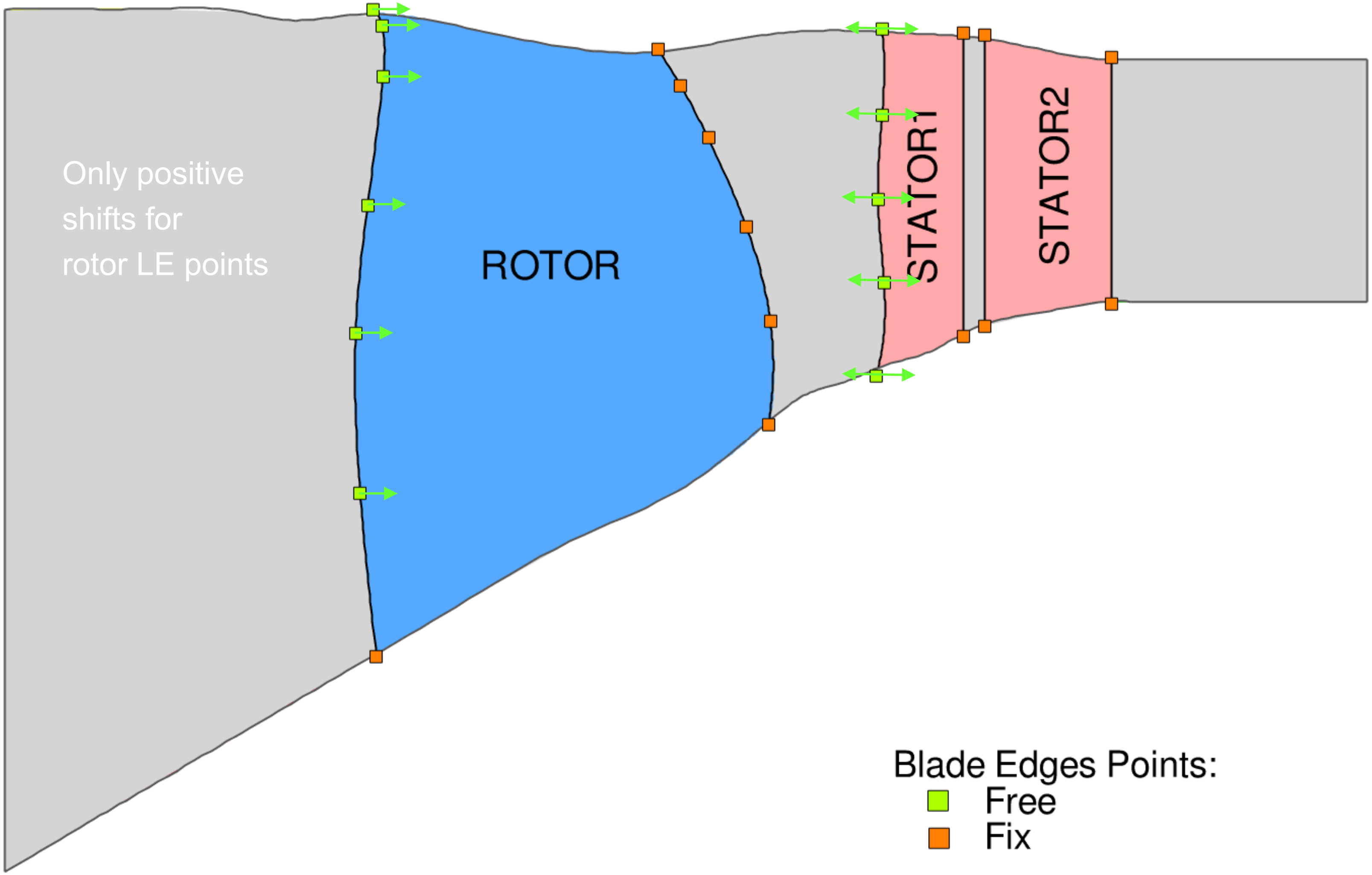
Pressure side parameterization by
a thickness distribution based on the
suction side

Maximum freedom for the profile geometries

→ All essential profile parameters were free for optimization

→ 188 free parameters for 14 construction profiles

Free Parameters - Axial Blade Positioning



Only positive shifts for rotor LE points

Blade Edges Points:
- 🟩 Free
- 🟧 Fix

Free Parameters - Circumferential Blade Positioning

Rotor:

Circumferential shift of construction profiles as radial distribution

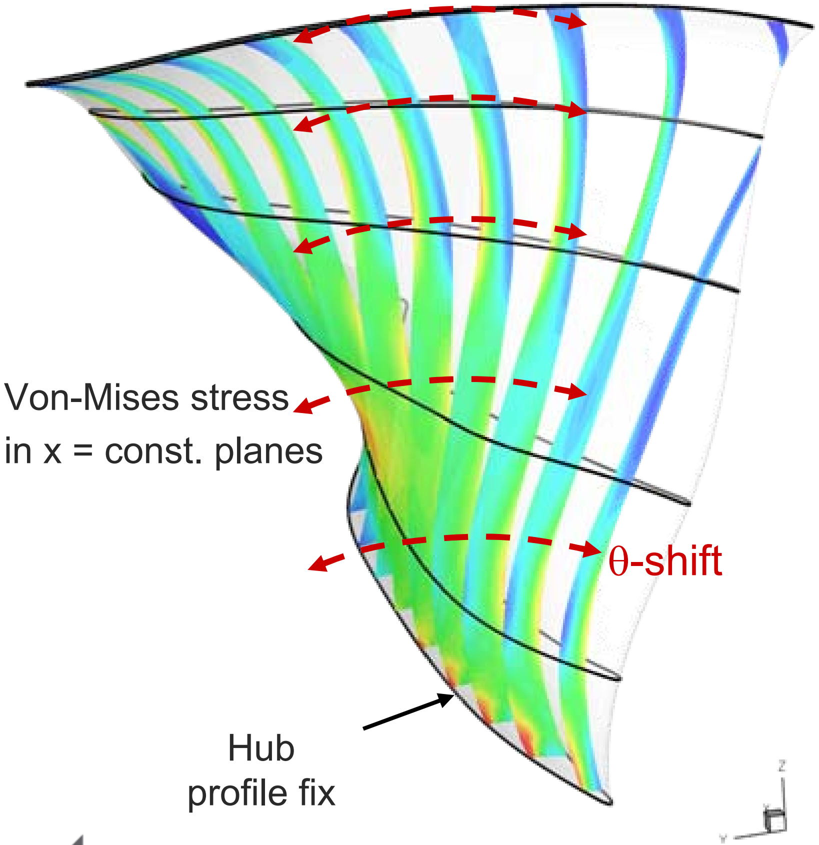
→ Blade balancing for structural mechanics

Stator:

Circumferential shift of construction profiles

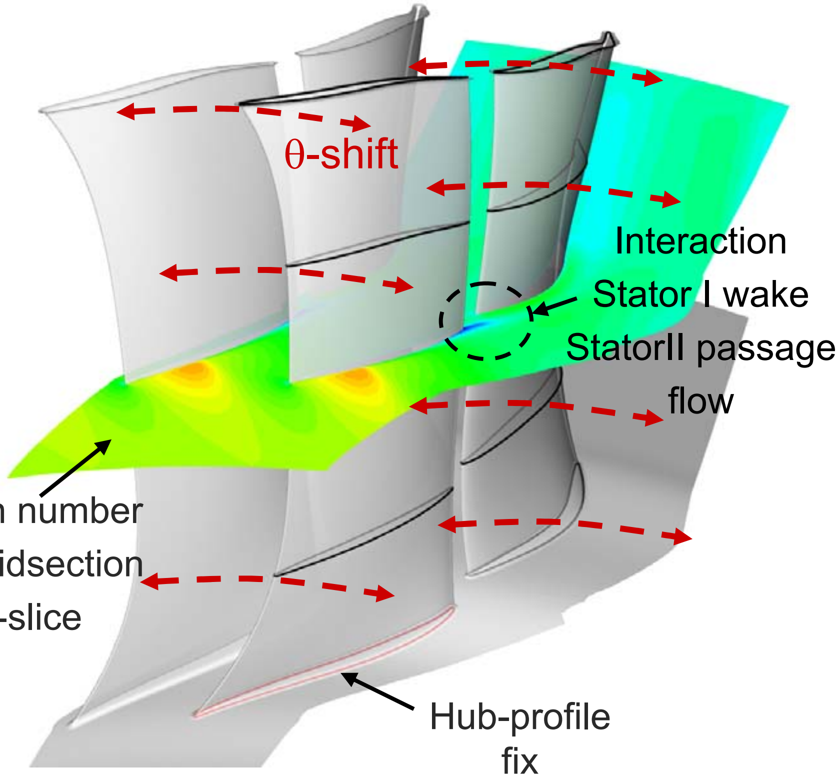
→ Relativ-positioning of stator rows

→ Lean- / Bow-optimization



Von-Mises stress in x = const. planes

Hub profile fix



Interaction Stator I wake StatorII passage flow

Mach number on midsection k-slice

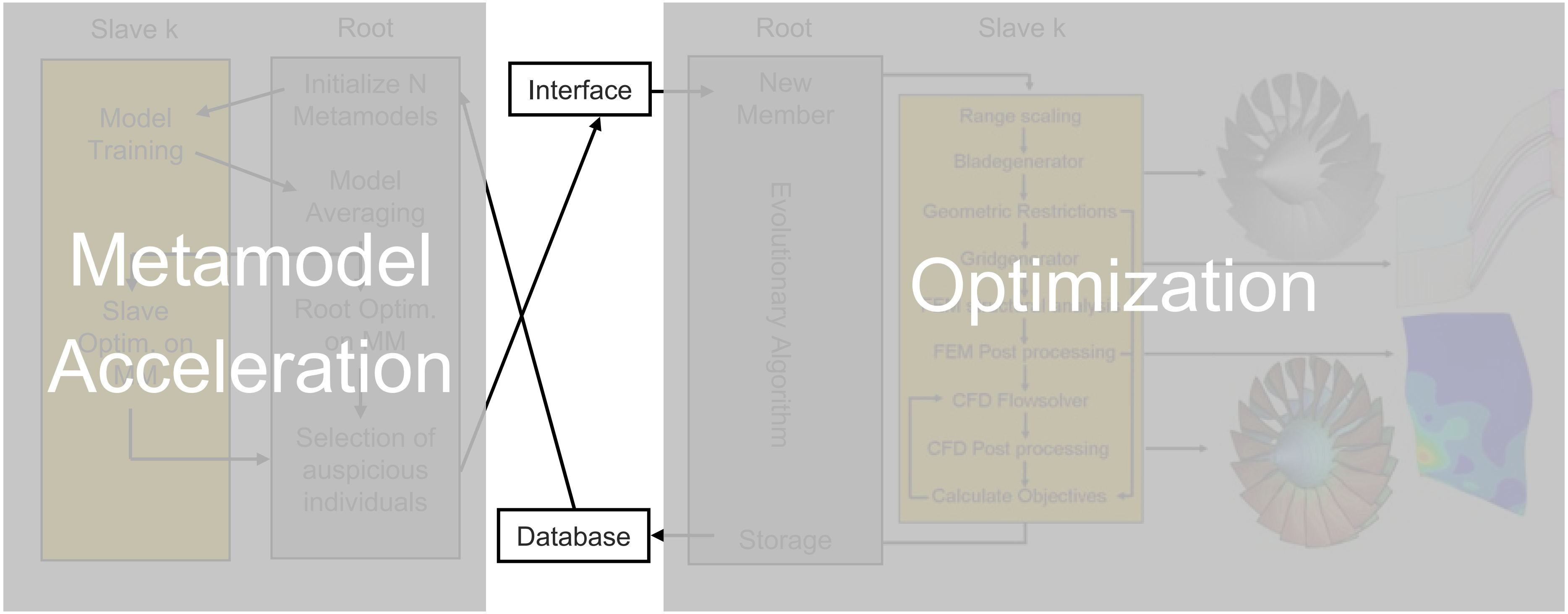
Hub-profile fix

Optimization Procedure

Rough structure of AutoOpti framework

Acceleration (MPI-parallelized)

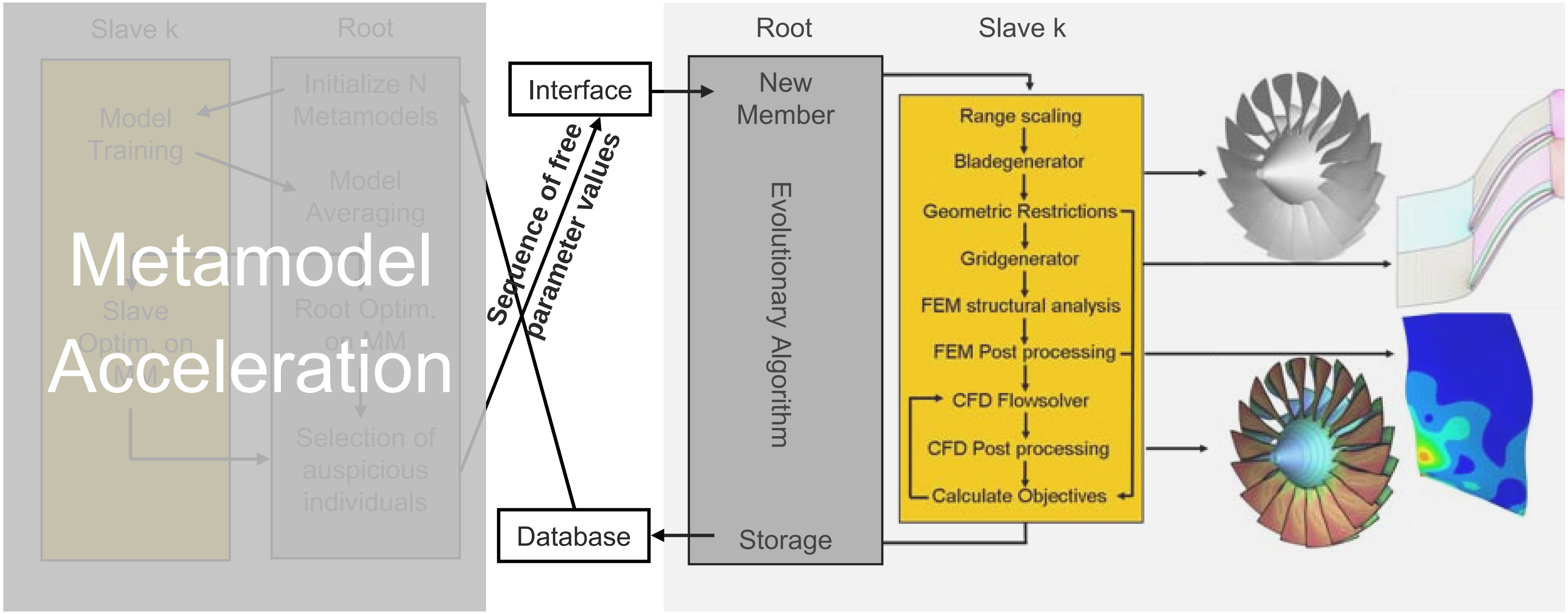
Optimization (MPI-parallelized)



Optimization Flow Chart

Acceleration (MPI-parallelized)

Optimization (MPI-parallelized)



Slave k

Root

Model Training

Initialize N Metamodels

Model Averaging

Slave Optim. on MM

Root Optim. on MM

Selection of auspicious individuals

Metamodel Acceleration

Interface

Database

Sequence of free parameter values

Root

Slave k

New Member

Evolutionary Algorithm

Storage

Range scaling

Bladegenerator

Geometric Restrictions

Gridgenerator

FEM structural analysis

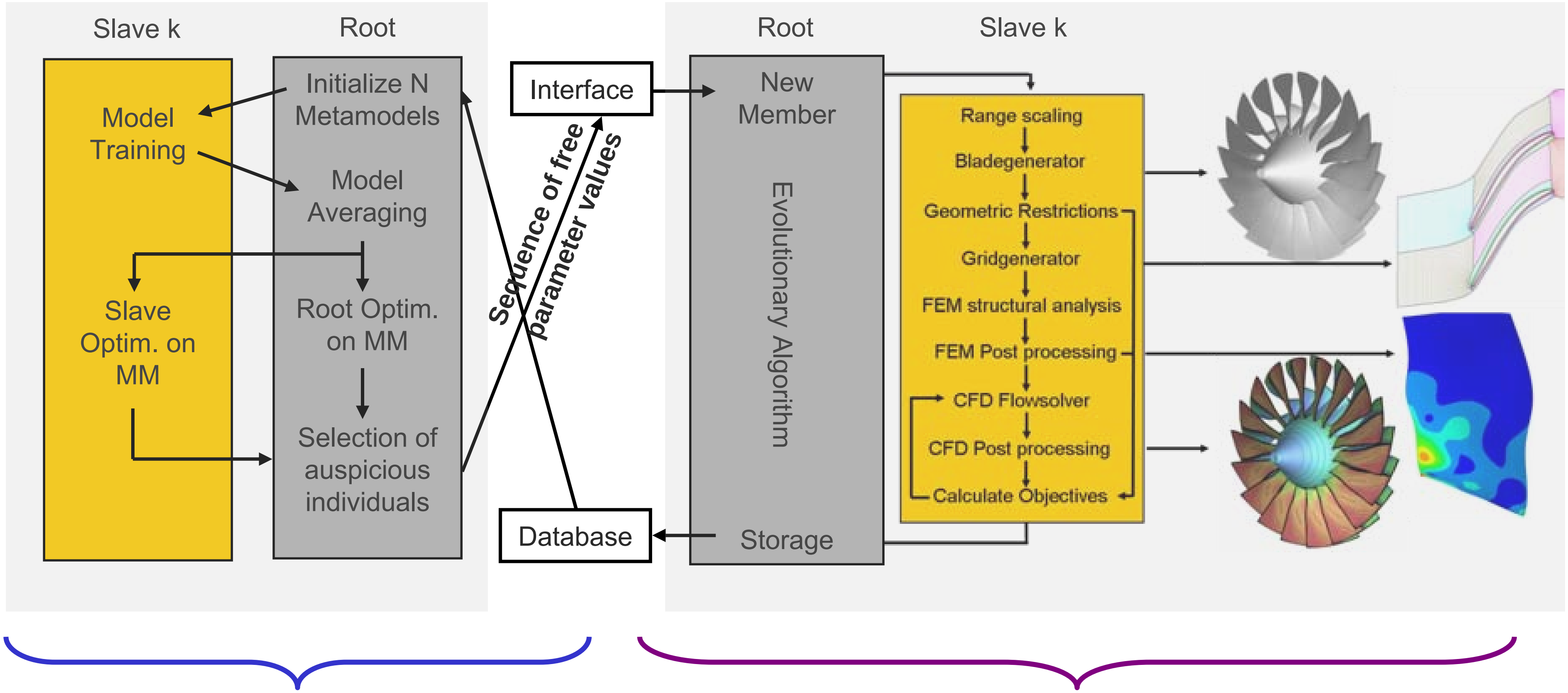
FEM Post processing

CFD Flowsolver

CFD Post processing

Calculate Objectives

Optimization Flow Chart



Acceleration (MPI-parallelized)

Optimization (MPI-parallelized)

Slave k

Model Training

Slave Optim. on MM

Root

Initialize N Metamodels

Model Averaging

Root Optim. on MM

Selection of auspicious individuals

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CFD Post processing

Calculate Objectives

~25% computational effort

~75% computational effort

Optimization Setup

- Overall 231 free parameters with prospect of only a few thousend fitness evaluations

  ➔ impossible to find THE OPTIMUM!

  ➔ Small steps in the right direction with a setup, which potentially solves the problem

- Parameterization:
  - Identify critical design parameters and the needed resolution (radial, axial, …)
  - Validity of compressor configurations (geometrical, mechanical, fabricational, …) ideally by the parameterisation and parameter limits, to avoid high dump rates, slowing down the process.

- Optimization:
  - EA combined with sophisticated acceleration procedures
    - Start of metamodel acceleration after ~100 members by GA
    - A separate metamodel collective is trained for every parameter (flow-, performance-, FE-, convergence – „binary Metamodel“) needed for fitness or constraint formulation.

Objectives / Restrictions

Objectives:

- Objective 1: $F1 = -0.5 * (\eta_{is,WL_{100\%rpm}} + \eta_{is,WL_{79\%rpm}})$

- Objective 2: $F2 = -0.5 * (SM_{100\%rpm} + SM_{79\%rpm})$

Constraints:

- Mass Flows (2): $| \text{Mass flow}_{OP2/3} - \text{Mass flow}_{OP2/3,target} | < \text{Mass flow}_{tolerance}$

- Stage Exit Swirl: $\int |\alpha_{exit} - \alpha_{exit,target}| \, dm_{rel} < \alpha_{tolerance}$

  (Mass weighted absolute value of exit swirl angle deviation from target)

- Von-Mises Stress (Structural Mechanics): $\text{vonMises}_{max} < \text{vonMises}_{limit}$

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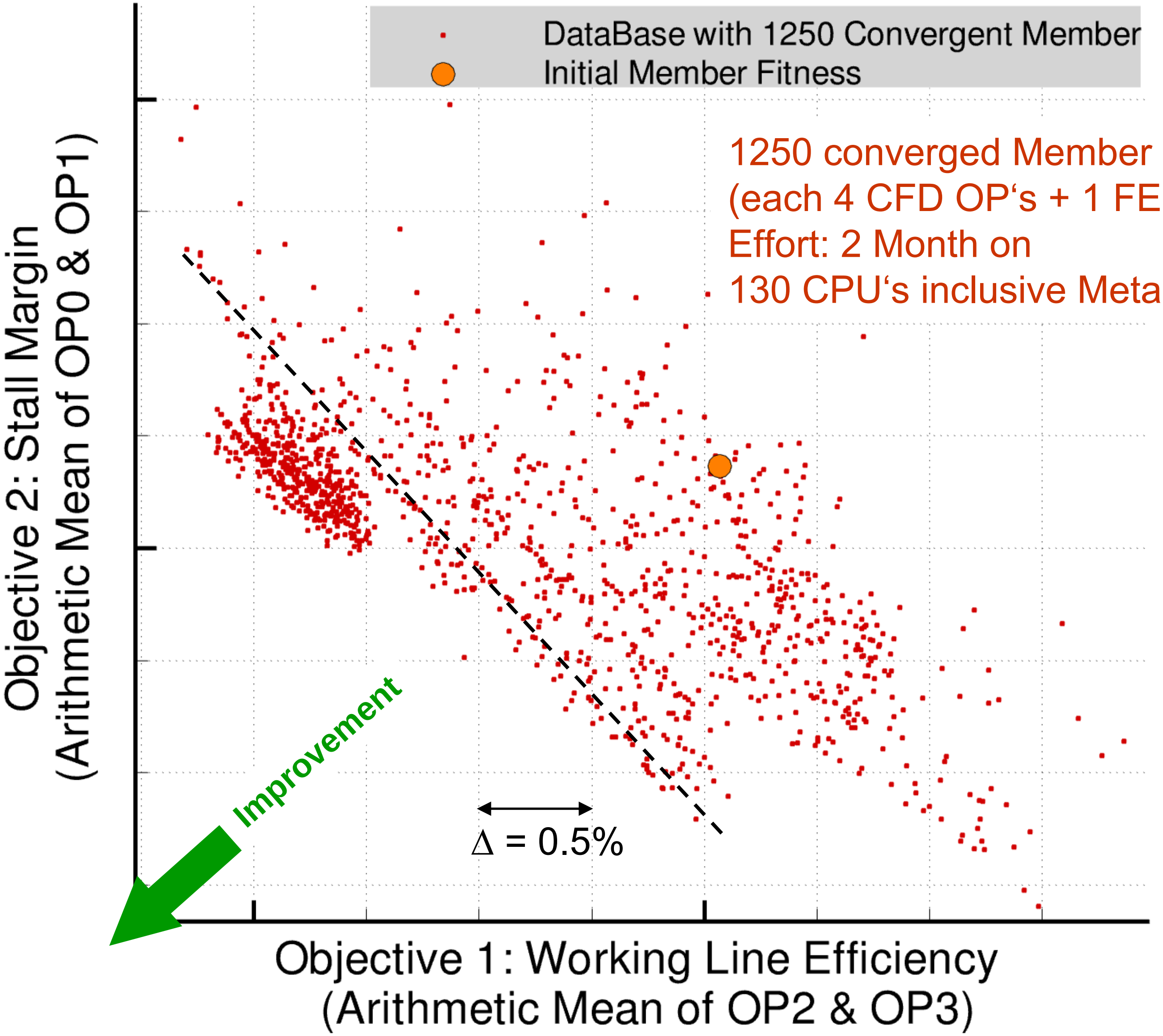
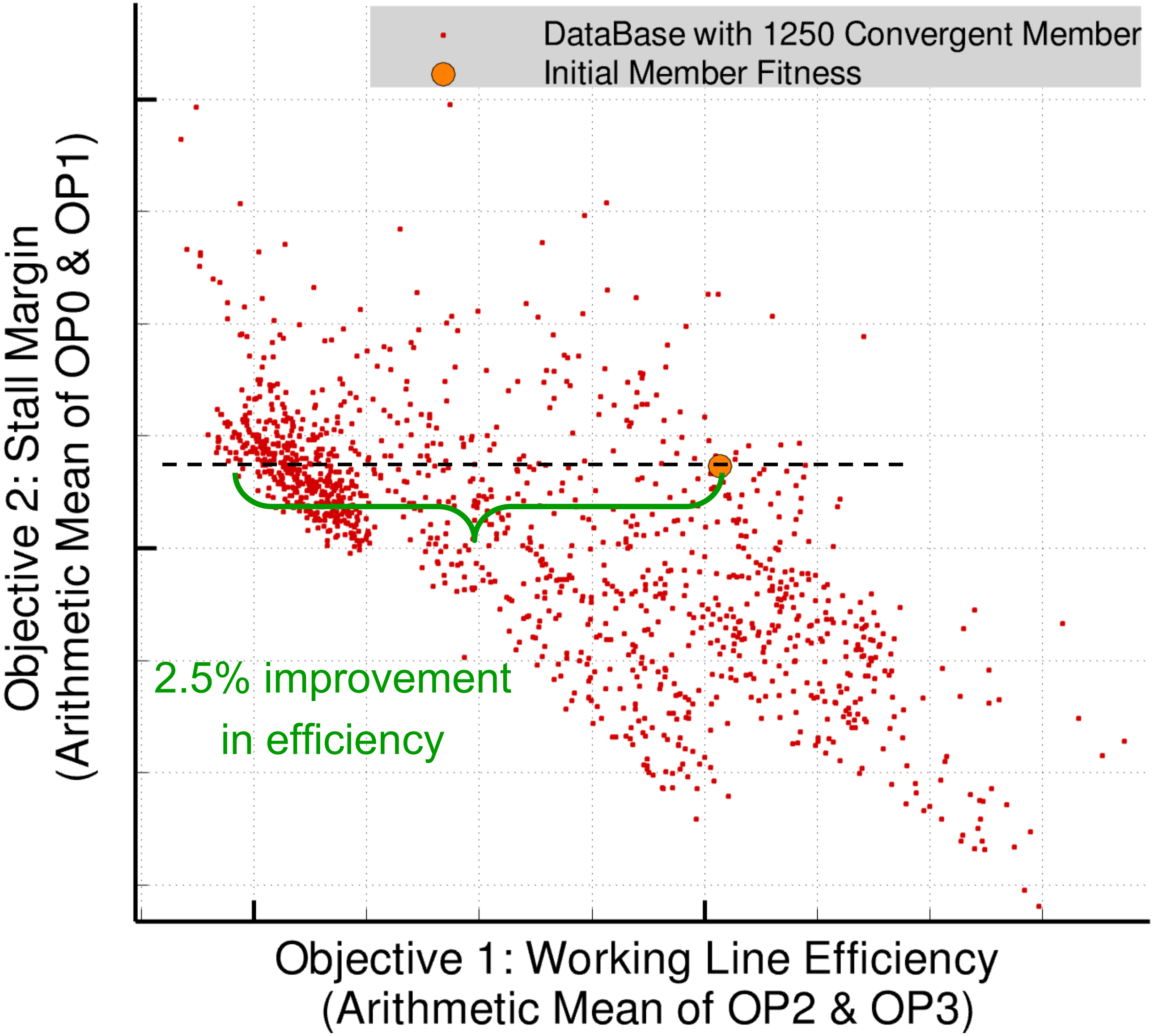
Database

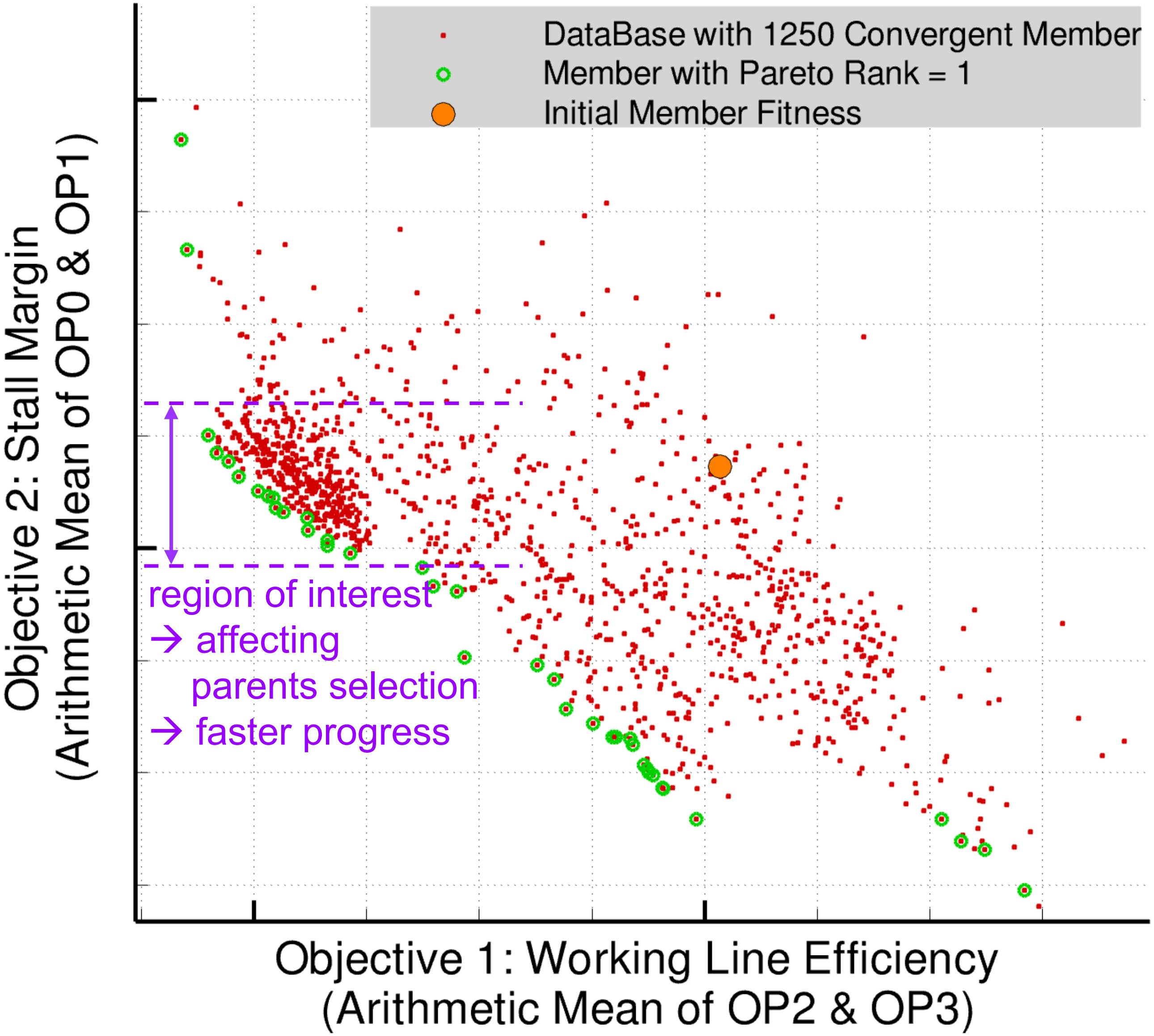


1250 converged Member
(each 4 CFD OP‘s + 1 FE-Analysis)
Effort: 2 Month on
130 CPU‘s inclusive Metamodels

Efficiency Improvement

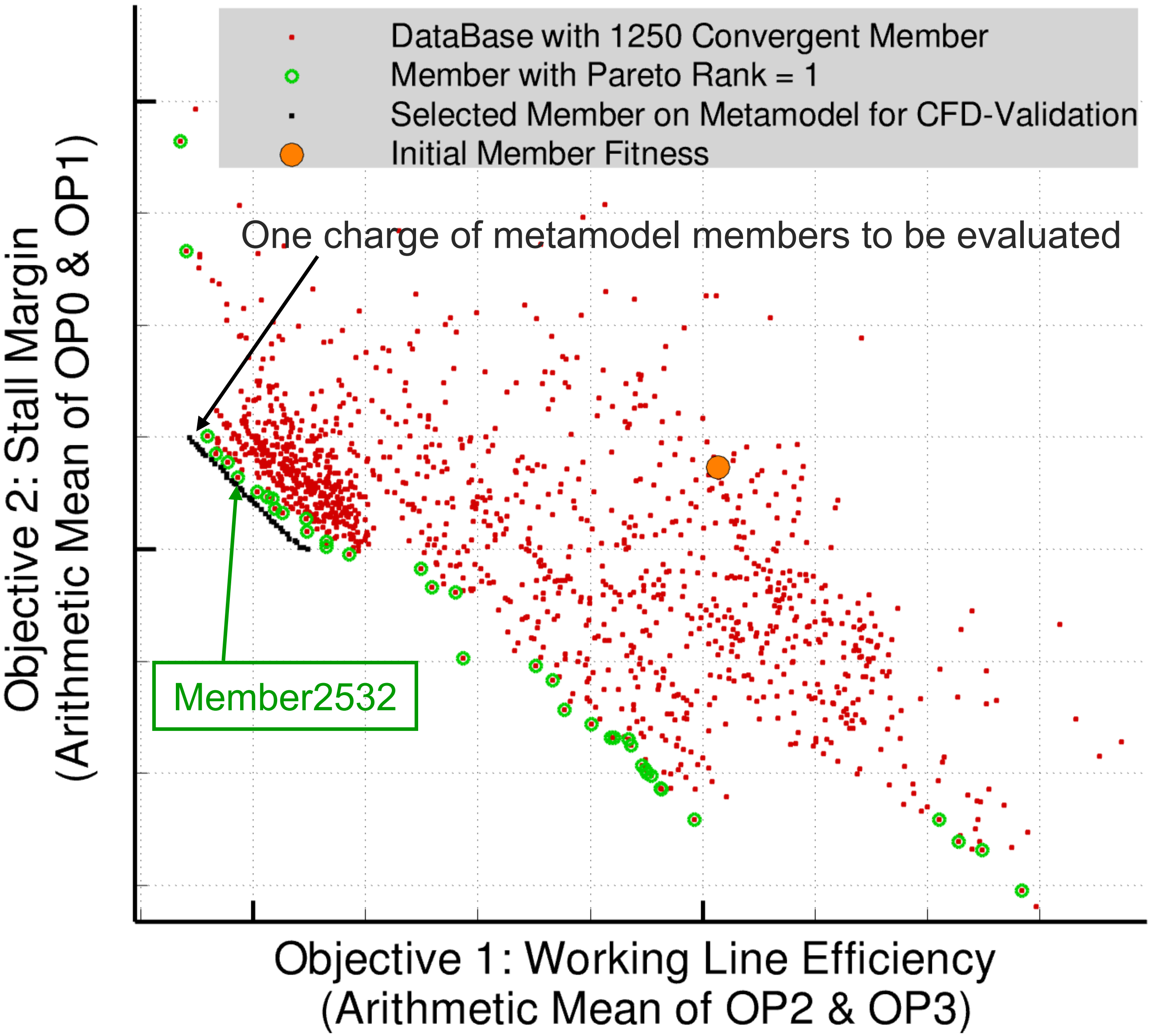


Pareto Front

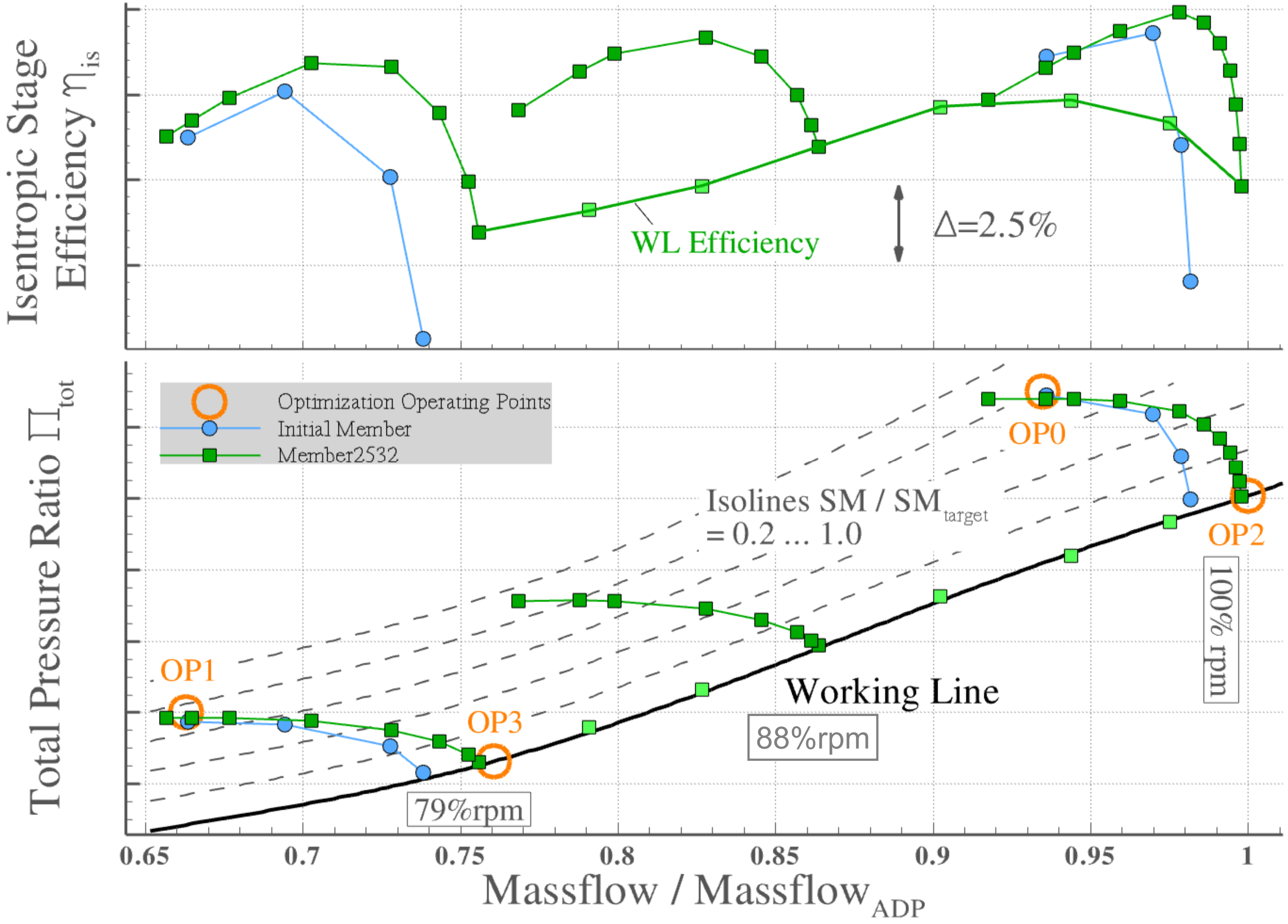


region of interest
→ affecting
parents selection
→ faster progress

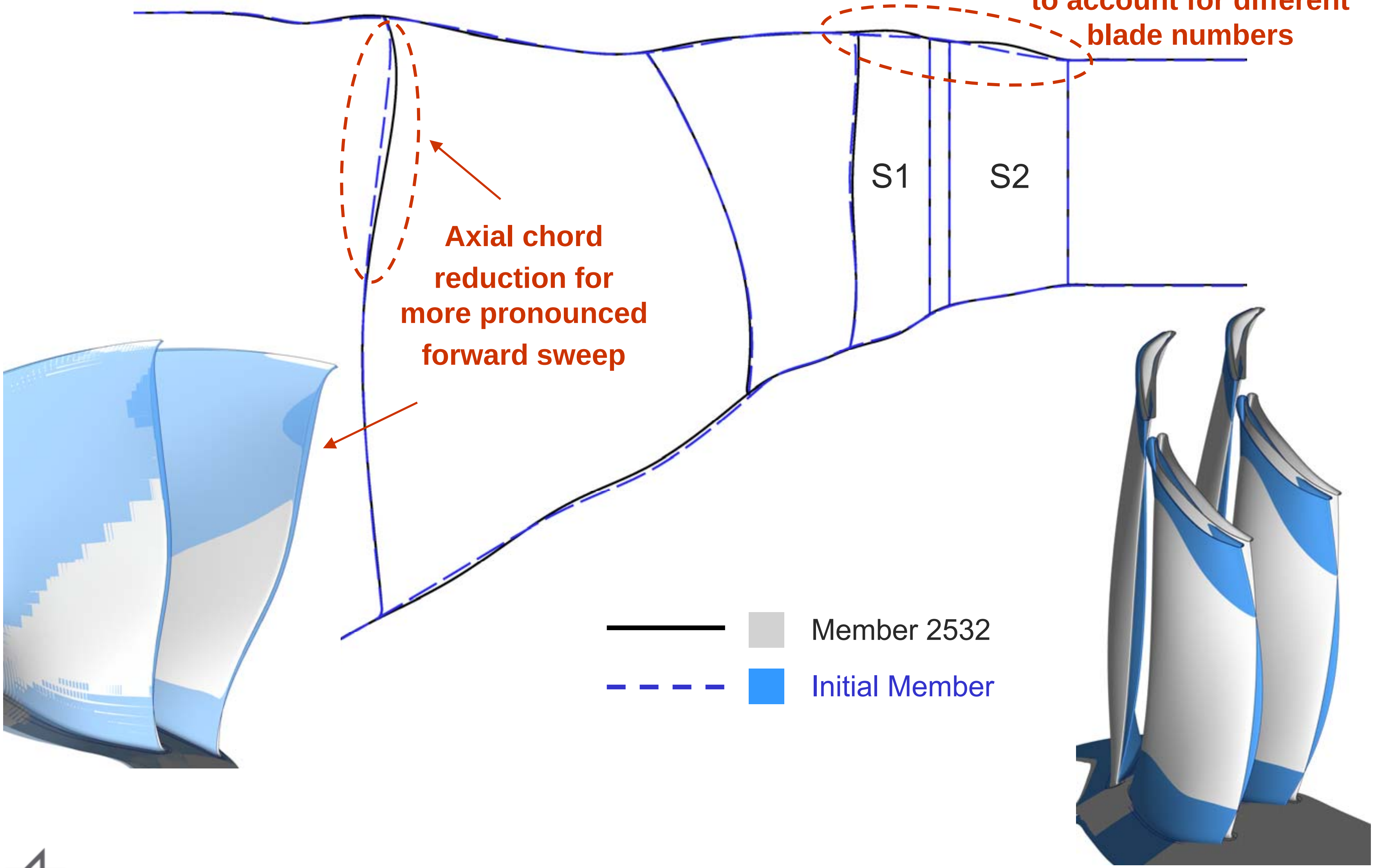
Metamodel Prediction / Final Member Selection



Optimized Performance Map



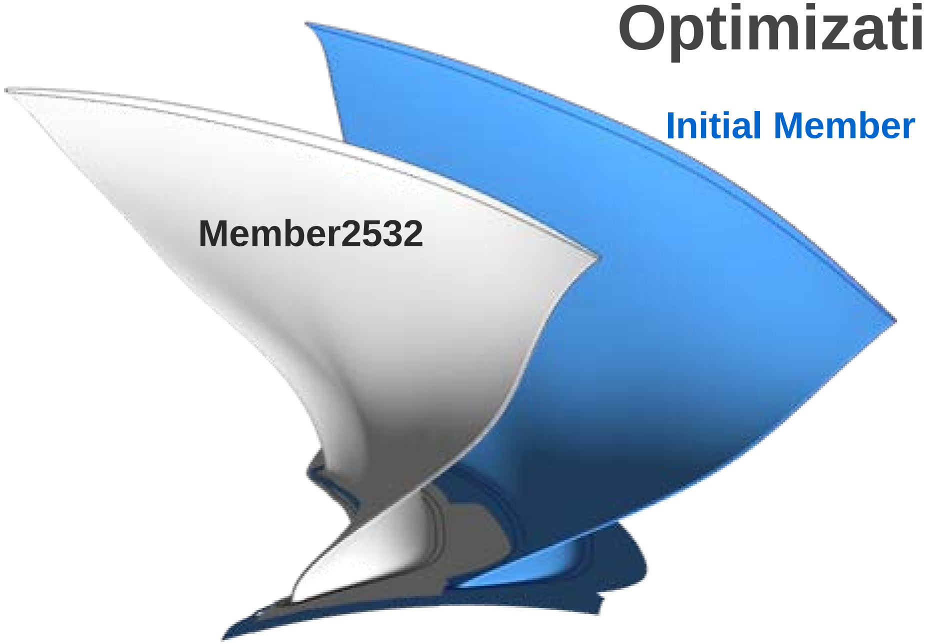
Optimization Results - Geomtries

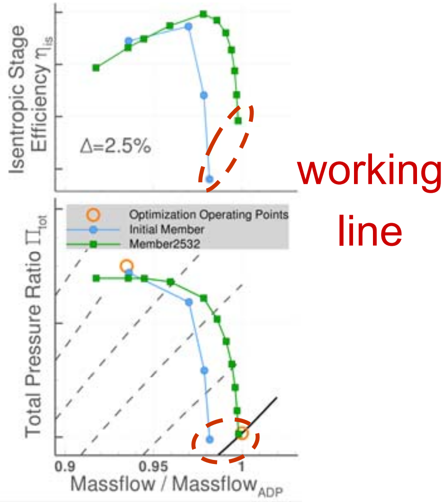


Endwall contouring to account for different blade numbers

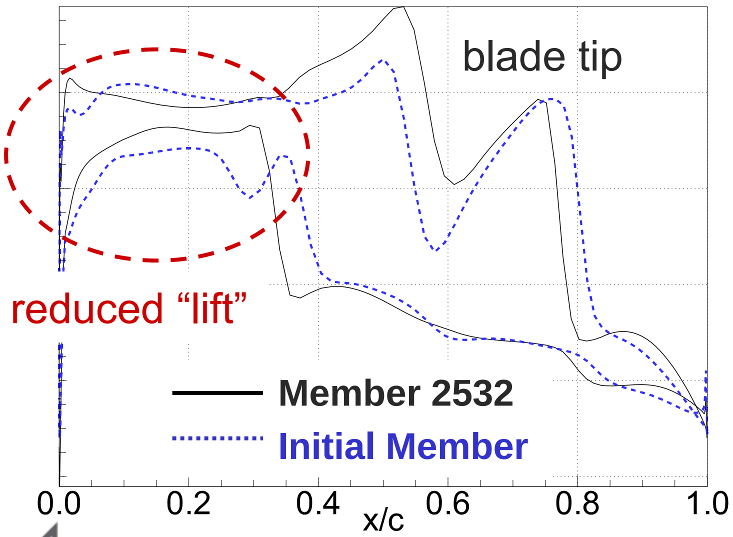
Axial chord reduction for more pronounced forward sweep

Optimization Results

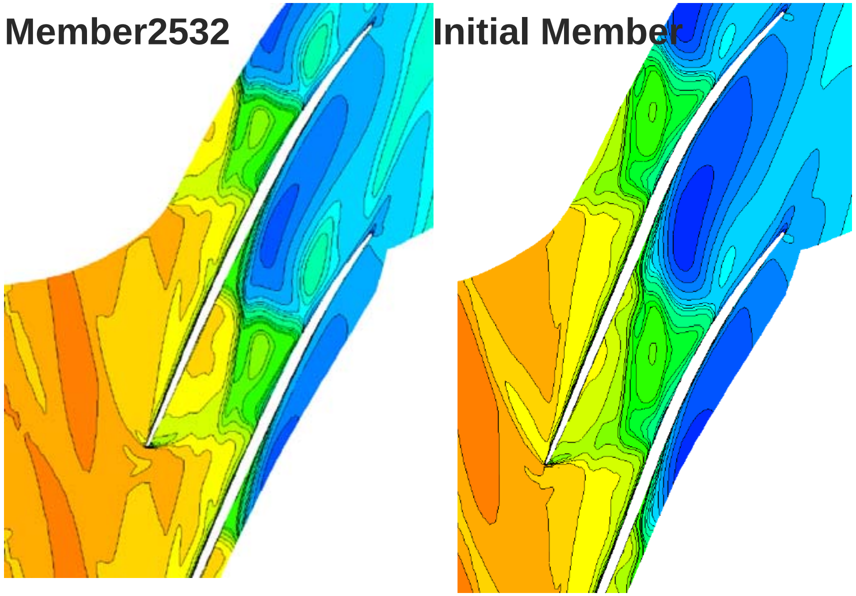




Rotor profile Mach number

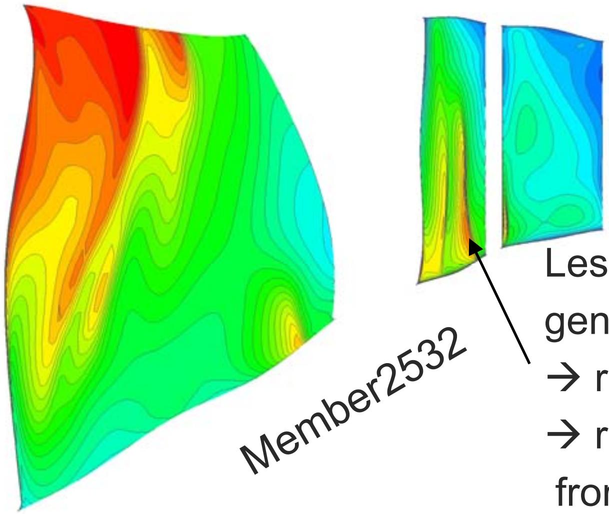


Blade-to-Blade Mach number @ rotor blade tip



Optimization Results

Isentropic Mach number on blade suction sides

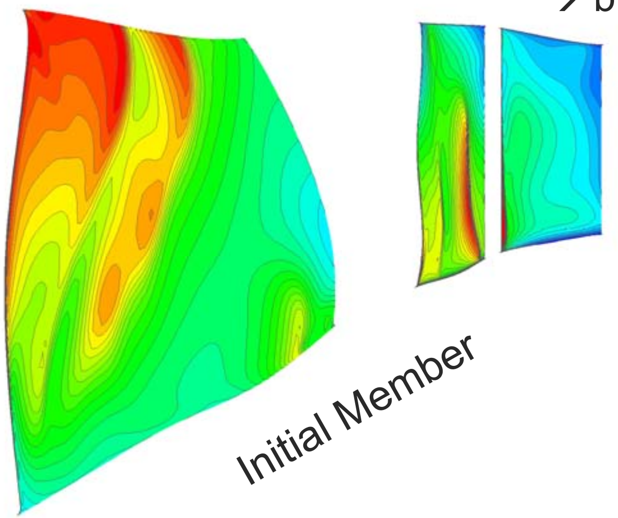


Less rotor total pressure generation

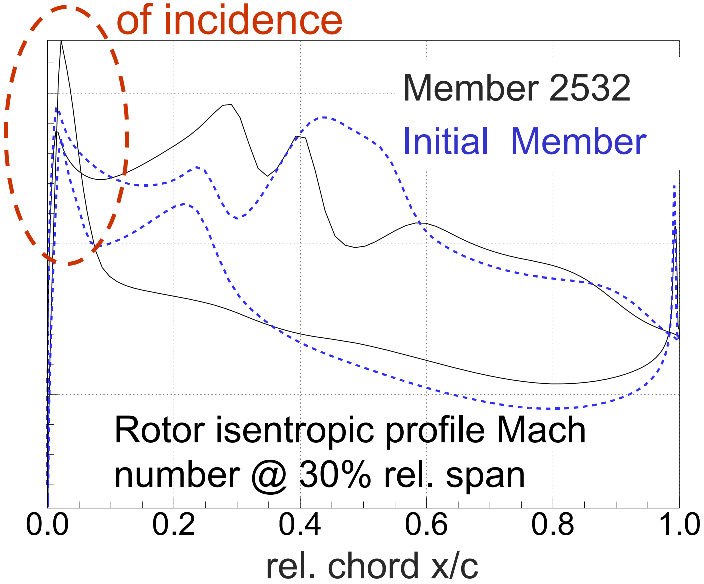
→ reduced shock losses

→ reduced visous losses from shock BL-interaction

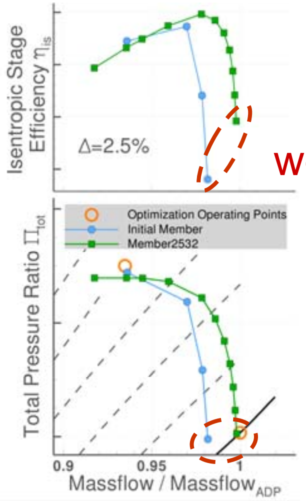
→ but same Π near stall



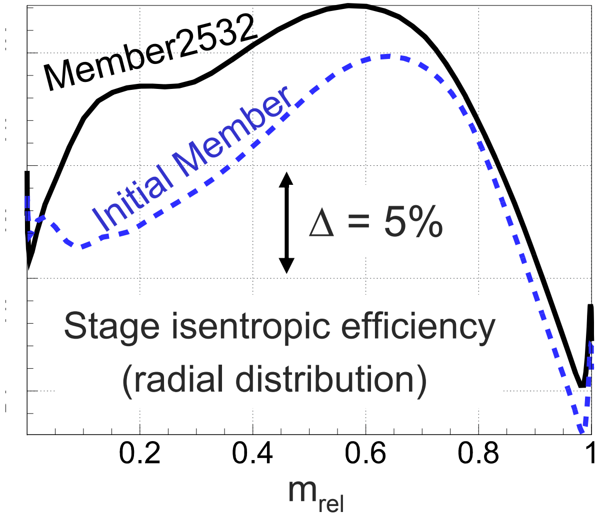
change of incidence



Rotor isentropic profile Mach number @ 30% rel. span



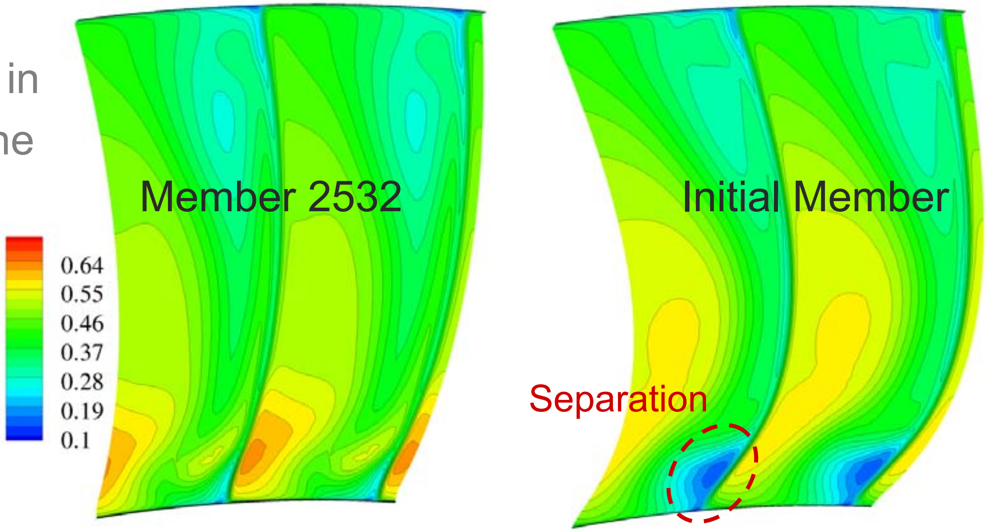
working line



Stage isentropic efficiency (radial distribution)

Optimization Results

Mach number in
x = const. plane
@ statorII TE



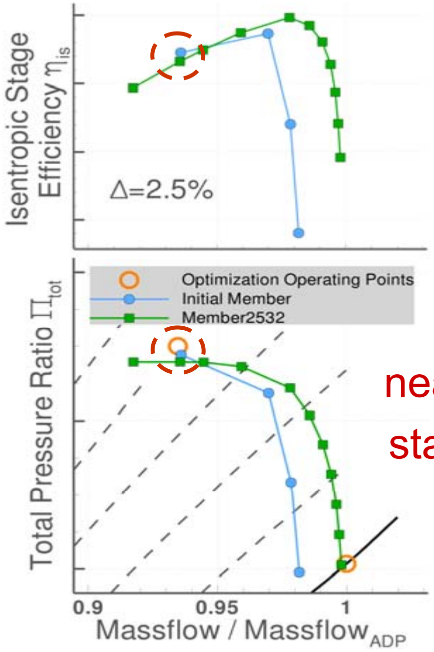
Member 2532

Initial Member

Separation

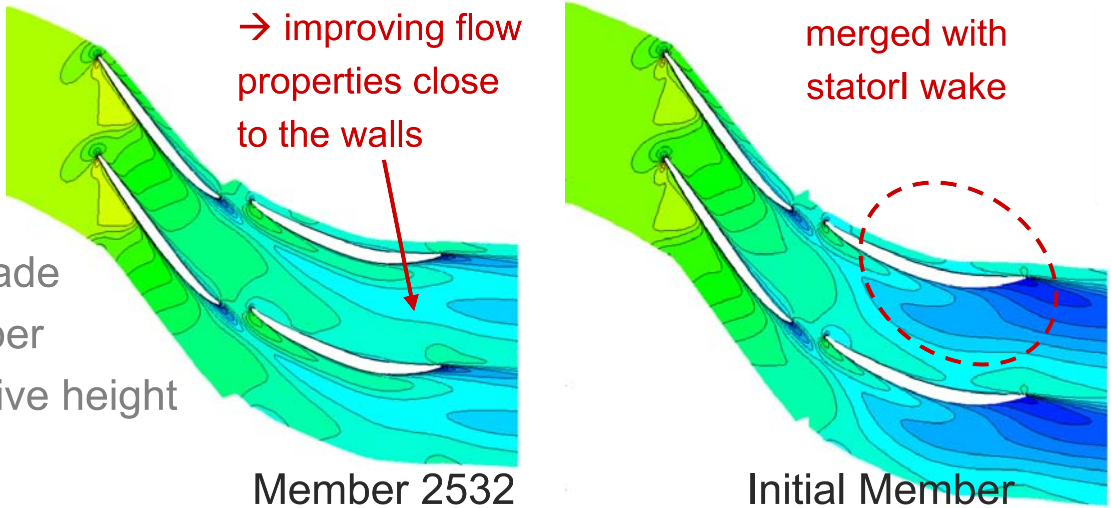
Centered wake
at statorII TE
→ improving flow
properties close
to the walls

Low momentum fluid
from the hub surface
merged with
statorI wake



near
stall

Blade-to-blade
Mach number
@ 5% relative height



Member 2532

Initial Member

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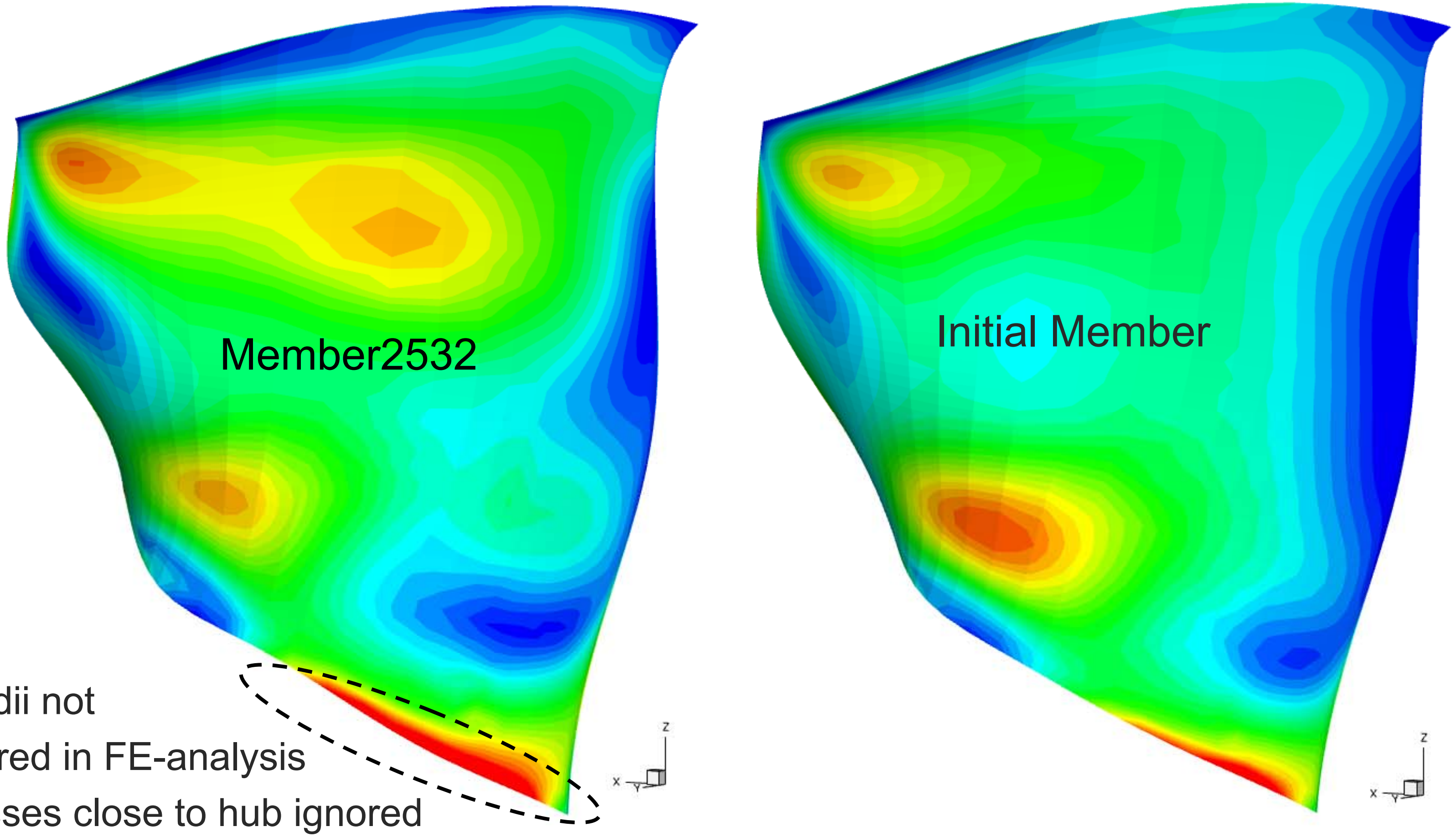
Rotor Mechanical Stress Distribution

- Thanks considering the rotor mechanical stresses, blade feasibility has been preserved.



Fillet-radii not considered in FE-analysis

→ Stresses close to hub ignored

→ Appropriate fillet solves this issue

Conclusion

- A highly loaded, transonic fan was successfully optimized in a multidisciplinary approach with the very high number of 231 free design parameters

  → Use of metamodels as accelerating techniques is crucial

- Aerodynamic Performance was considered for two rotational speeds with
  - Mass flow rates
  - Stall margin
  - Efficiency
  - Exit swirl

- Rotor static stresses were considered based on a finite element analysis

- Mass controlled operating points near stall are an efficient method to adress a kind of stall margin

  → High comparability between different member due to similar flow kinematics

  → Uncertainty of remaining stall margin

- After the presented optimization the rotors Campbell diagram has been optimized successfully, future optimizations might include that feature