Advanced 3D Geometries for Turbine Applications

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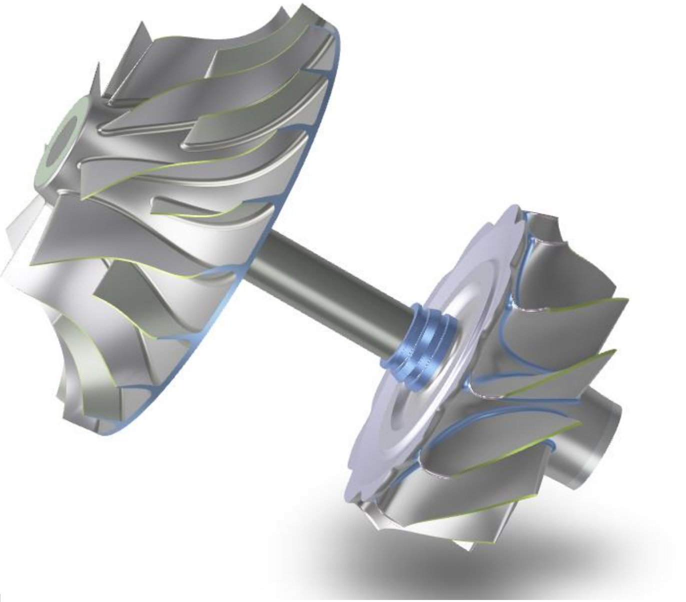
Advanced 3D Geometries for Turbine Applications

A **turbine** (from the Latin *turbo*, a vortex, related to the Greek τύρβη, *tyrbē*, meaning "turbulence") is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. The work produced by a turbine can be used for generating electrical power when combined with a generator or producing thrust, as in the case of jet engines.

- **Radial turbines**
  - Case study courtesy of MTU
  - Turbocharger, GAMMA R&D project
- **Axial turbines**
  - Case study courtesy of Siemens
  - Industrial gas turbine

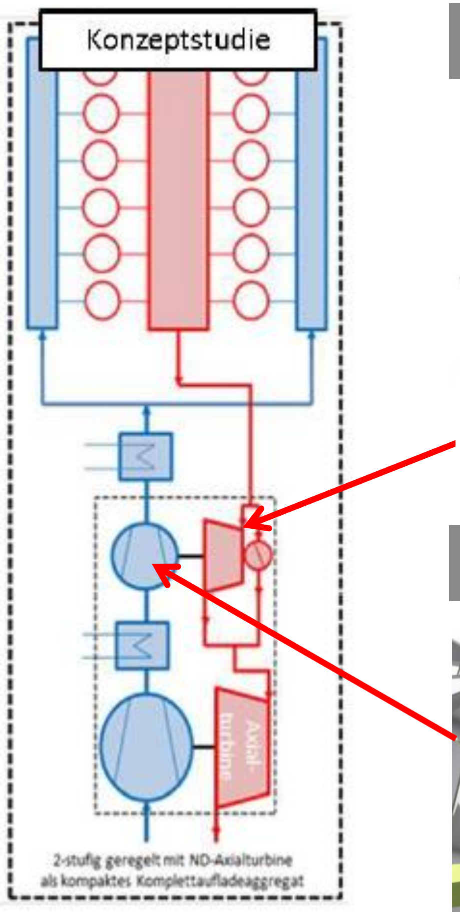
GAMMA R&D Project

- European R&D project (phase 1)
- GAMMA = Effiziente **GA**smotoren für **M**aritiM**e** **A**nwendungen
- Goal:
  - Investigate new technologies for turbochargers of high efficiency, novel fuel running (LNG / natural gas) engines
  - Increase efficiency, reduce carbon emissions (~7% in first project phase) , while staying cost effective by reducing the complexity of engine parts
- Field of application
  - Engines of 0.5 -10 MW
  - Yards, offshore supply vessel, patrol boats, trains, large trucks
- Project partners:
  - MTU Friedrichshafen GmbH, Numeca Ingenieurbüro, Friendship Systems AG, TU Darmstadt Fachgebiet Gasturbinen, Luft- und Raumfahrtantriebe



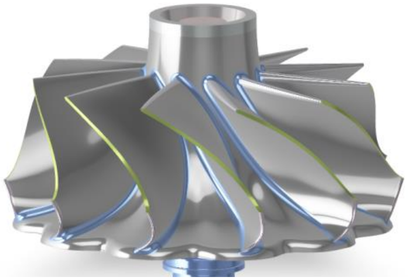
Engine and turbocharger schematic layout

- Engine concept
  - Two stage design
  - High pressure turbine and compressor
  - Low pressure axial turbine
  - High pressure bypass
  - Compact design
  - Modular parts

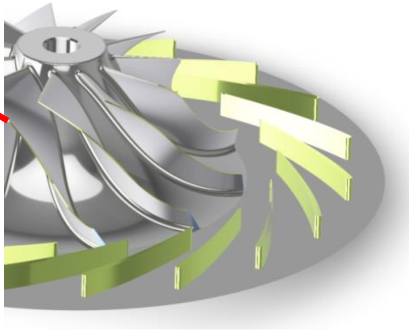


source: MTU Friedrichshafen GmbH

Radial turbine



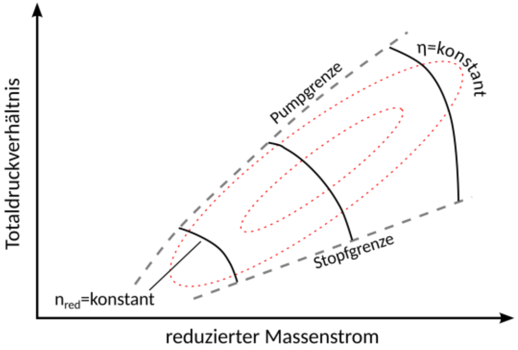
Compressor blades + diffusor

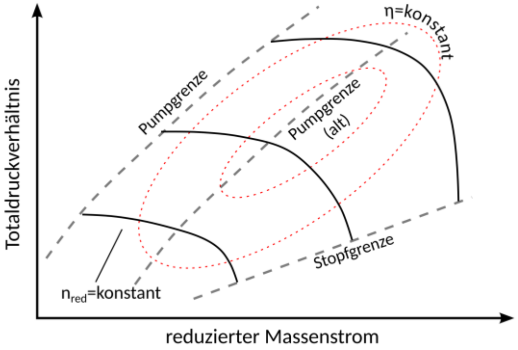


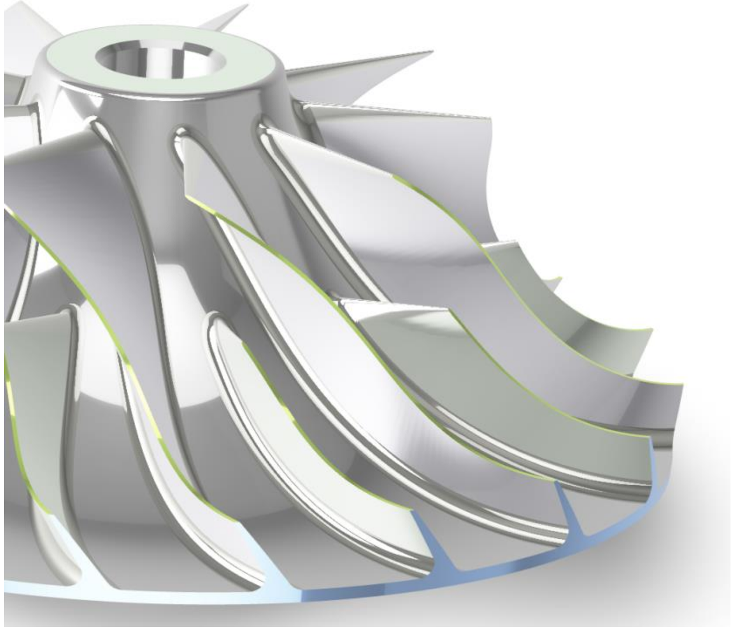
Compressor volute

Compressor

- Current baseline model has high efficiency but a limited operating range
- Target
  - Increase the range of operation
  - Maximize the efficiency
- Constraints
  - Eigenfrequency
  - Stresses
- Software:
  - Geometry: **CAESES**
  - Mesh CFD: AutoGrid (Numeca)
  - CFD: FINE/Turbo (Numeca)
  - Mesh FEA: SimLab (Altair)
  - FEA: CalculiX (Open source)
  - Optimization: modeFrontier (Esteco)

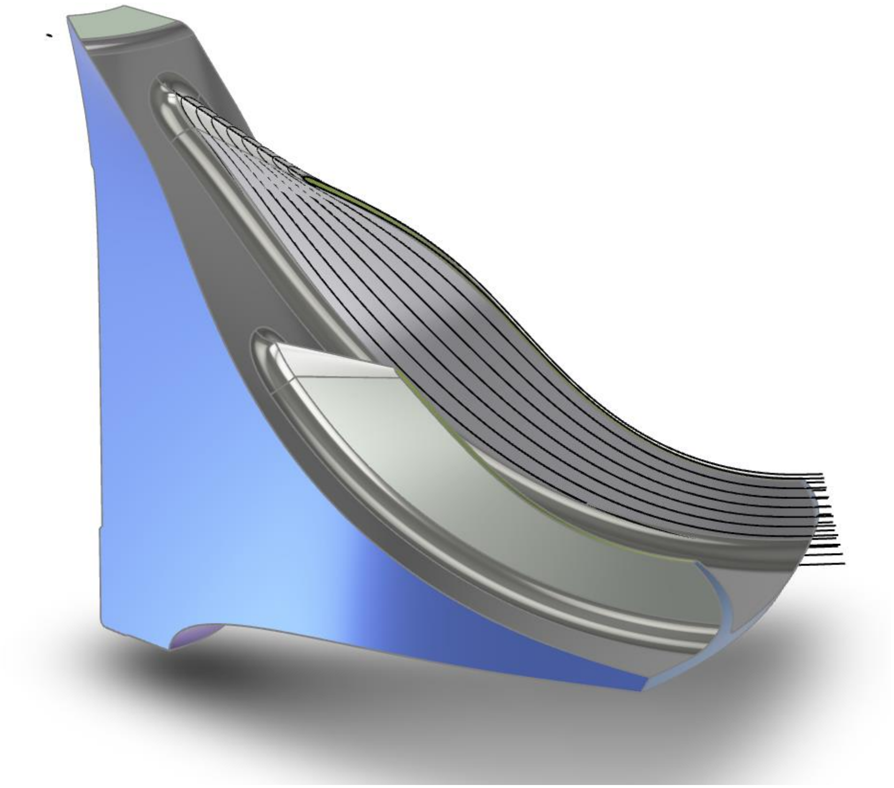


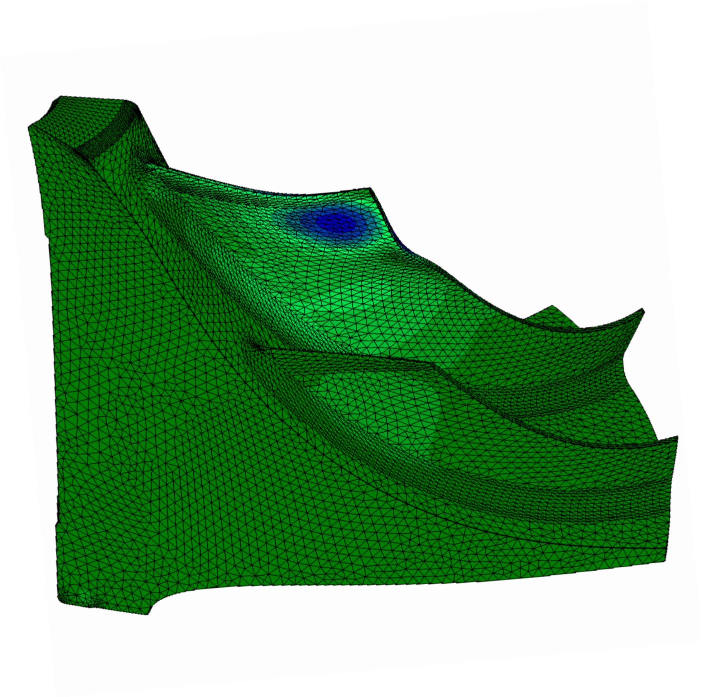




Compressor blades

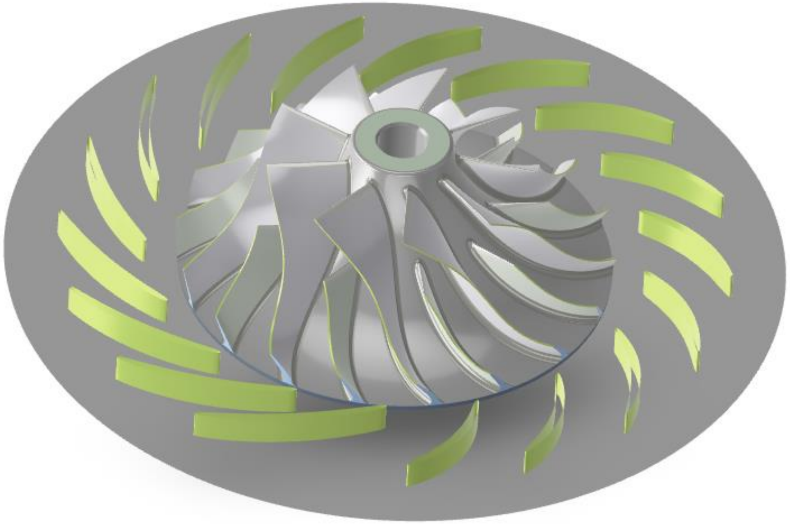
- High quality geometry outputs are needed for both structural mechanics and fluid dynamics
  - For CFD: blade sections exported in geomTurbo format (high quality mesh)
  - For FEA: Solid segments (periodic)

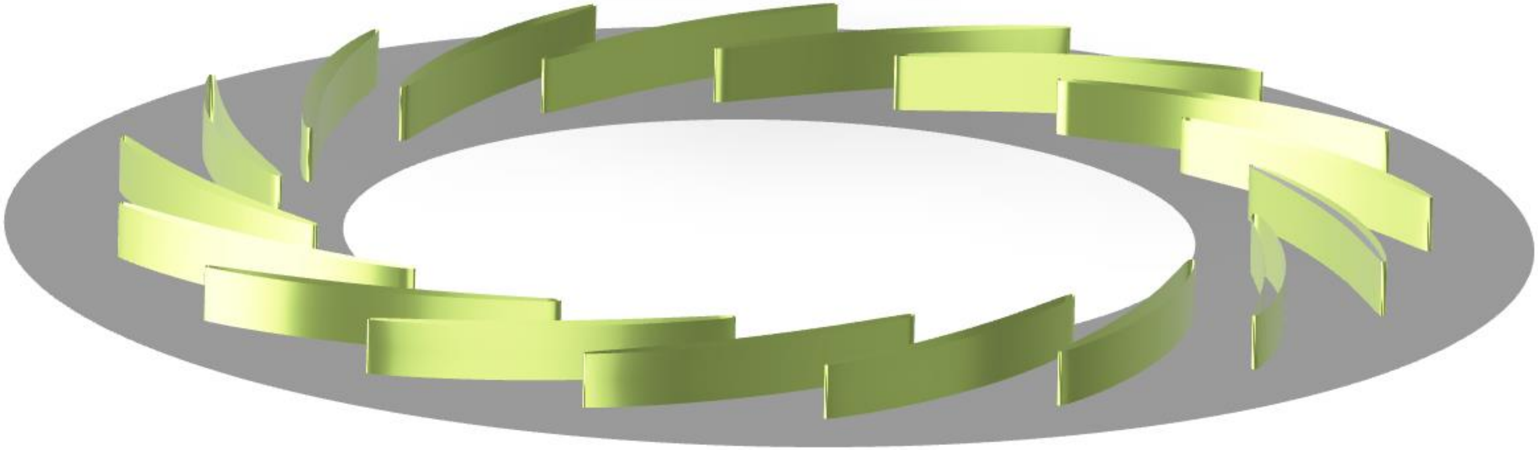




Diffusor vanes

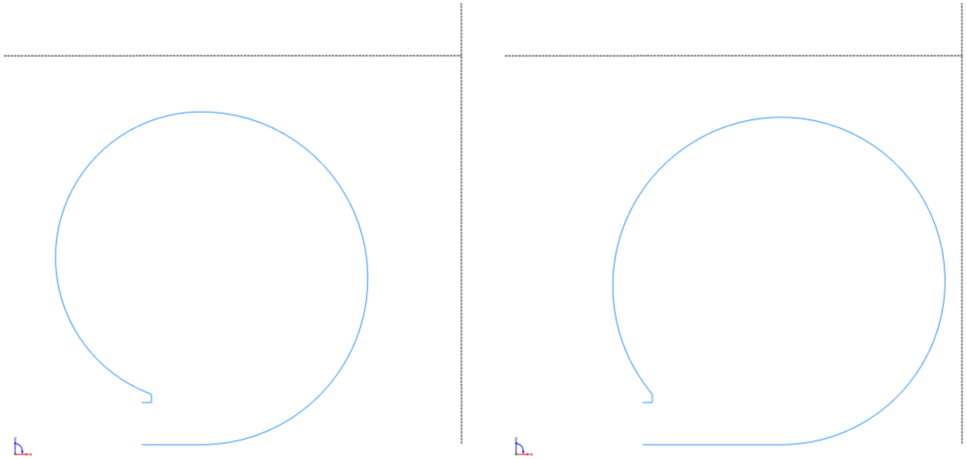
- Meta surface for each vane
- Setup is similar to the impeller blades
- Each parameter of the meta surface can also be varied in the circumferential direction
  - Curve engine and meta surface will be completely generated inside a *feature*
  - Inputs to the *feature* are parameter distributions (or constant values)

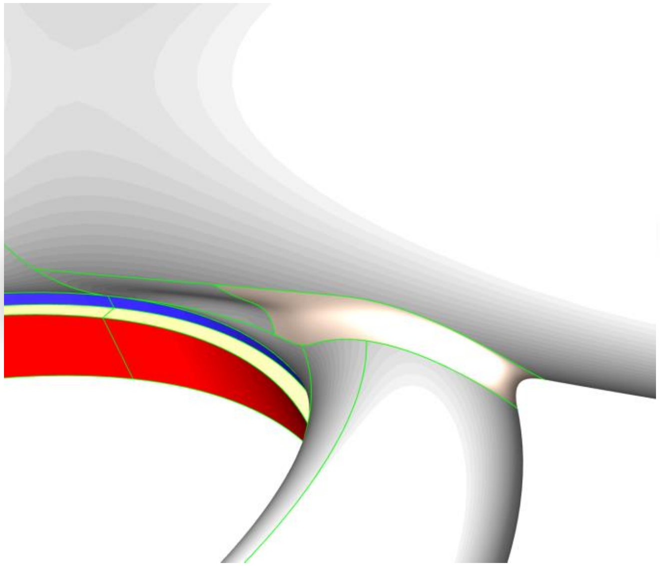




Compressor volute

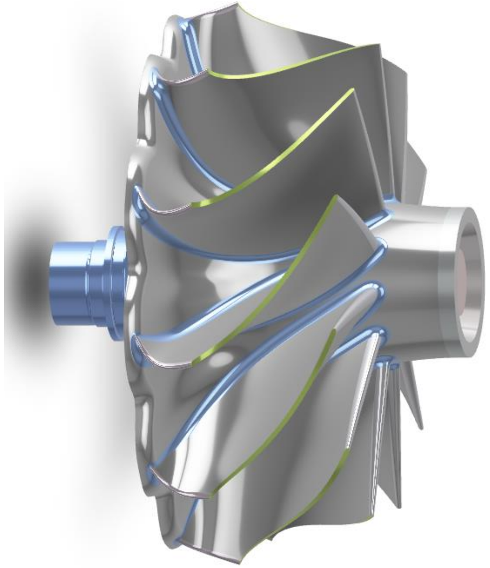
- Basic profile is modeled with circular segments
- The *board angle* and the *A2R* ratio can be varied
- If space constraint for the max radius is reached, then the profile is getting higher
- If the max height is reached, then the profile moves inwards
- Tongue modeled as a custom fillet surface that is robust and flexible

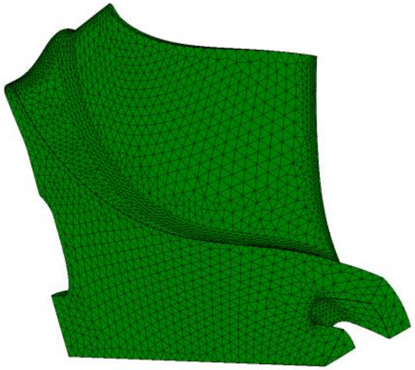


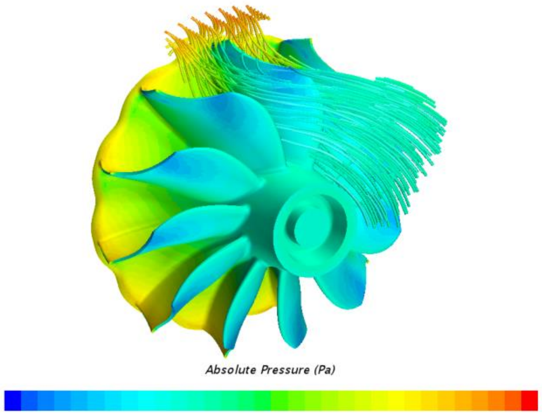


Turbine blades

- Target
  - Maximize the efficiency
- Constraints
  - Eigenfrequency
  - Stresses
  - Fatigue life
- Software:
  - Geometry: **CAESES**
  - Mesh CFD: STAR-CCM+ polyhedral
  - CFD: STAR-CCM+ (Siemens)
  - Mesh FEA: SimLab (Altair)
  - FEA: CalculiX (Open source)
  - Optimization: modeFrontier (Esteco)



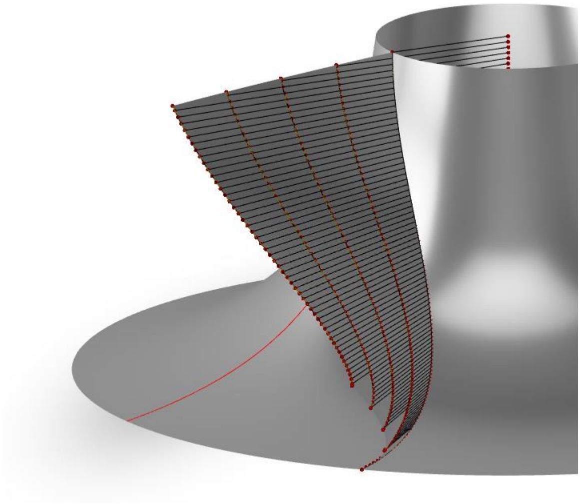




Turbine blades – Interesting features

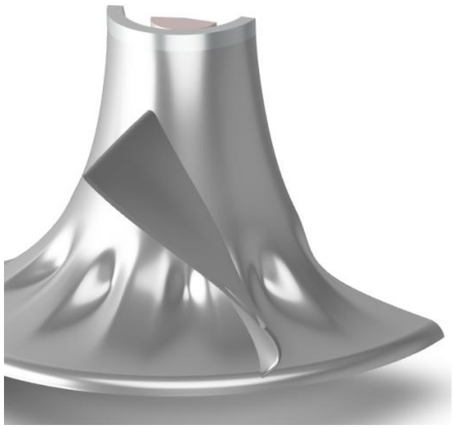
Camber surface

- All points *p* of the camber surface are dependent on the hub streamline
- p (theta,z)
- Structurally beneficial
- Reduces the number of design variables



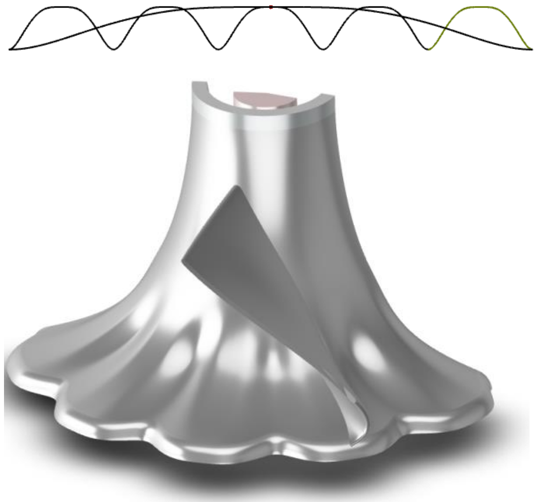
Hub profile contouring

- Hub profile can be changed in the circumferential direction
- Additional changes are possible, to apply profile contouring
- Beneficial in terms of reducing rotating mass, stresses



Hub Scallops

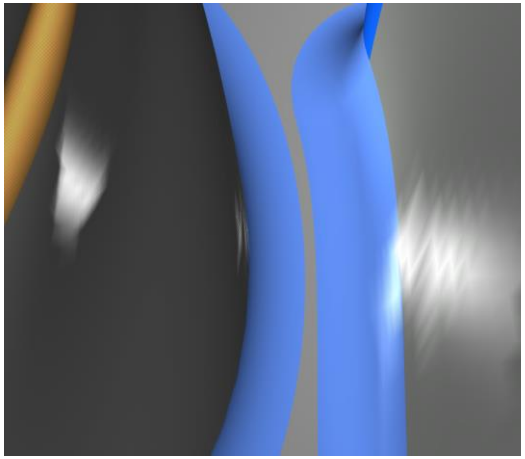
- Scallops are also directly included inside the hub surface
- Beneficial in terms of reducing rotating mass, stresses



Turbine blades – Interesting features

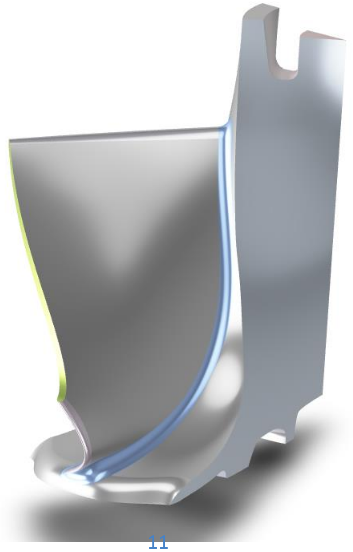
Max fillet radius

- For mechanical reasons it is beneficial to have a fillet radius between the blades that is as large as possible
- Maximum fillet radius and position are automatically calculated
- Internal optimization is used
- Variable radius fillets are being implemented



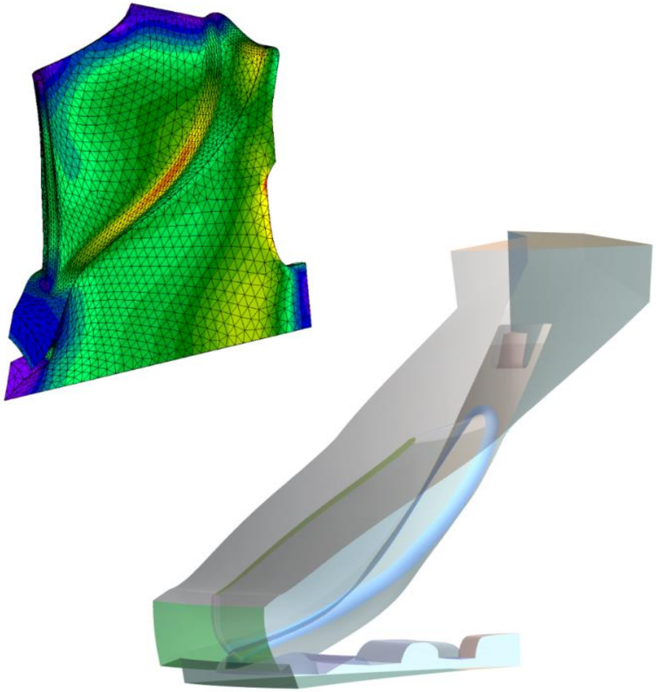
Periodic segment

- Periodic cut out is crucial between blades
- Working in domain space is very useful
- Consideration for generating high quality volume cells



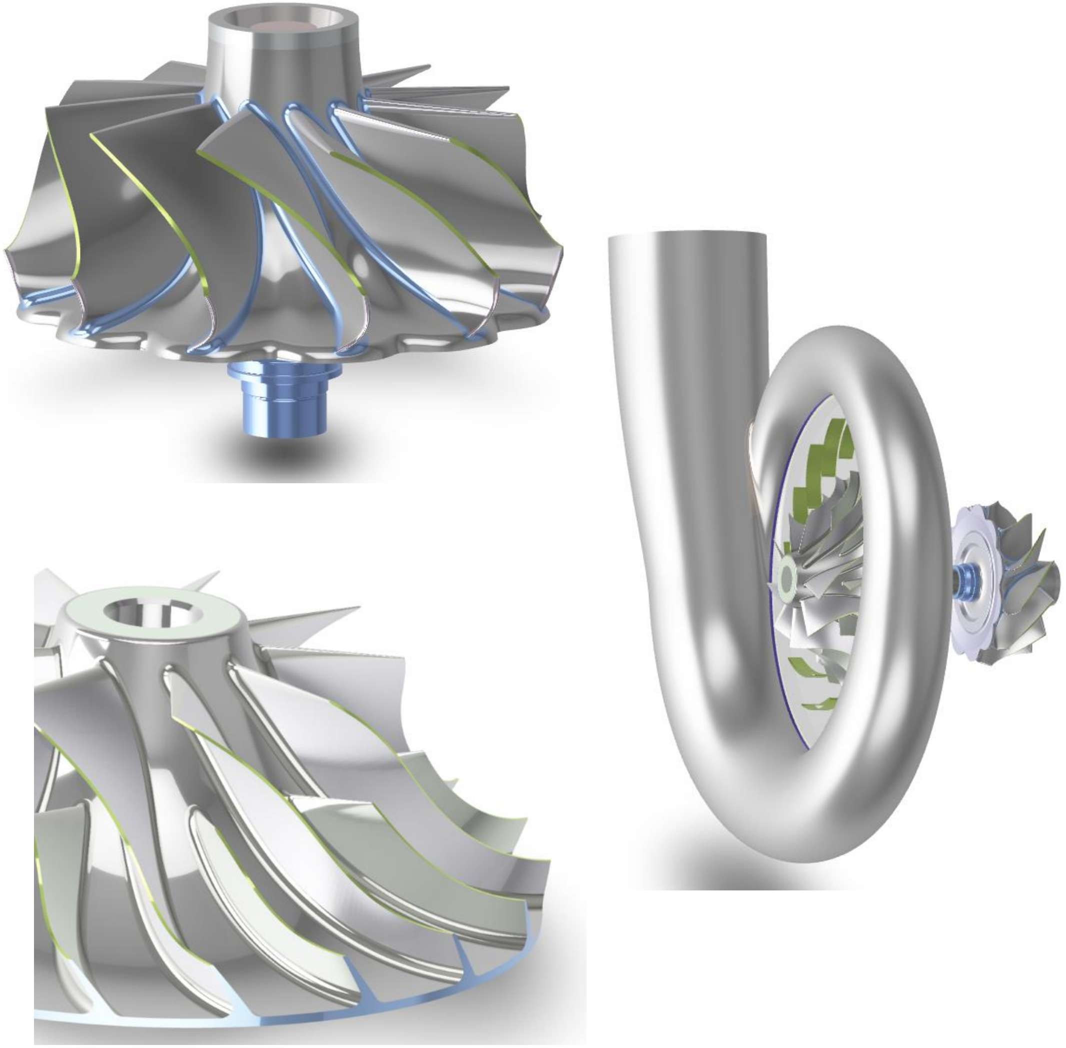
Flow domain

- For CFD
- Fluid and solid domain have to fit exactly to each other



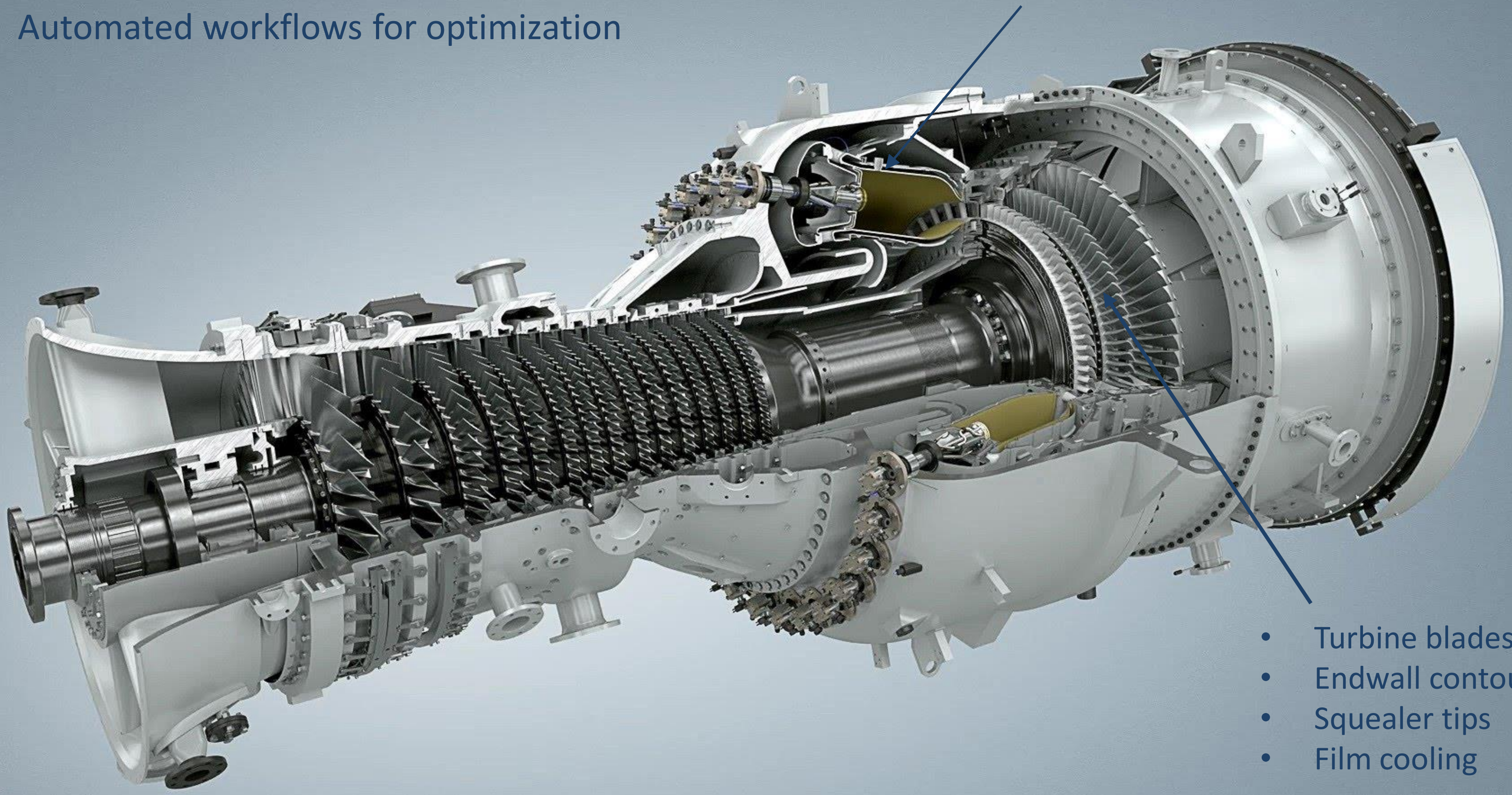
GAMMA – status & future work

- GAMMA is undertaking a study of next generation designs for large turbochargers
- CAESES is indispensable for creating flexible and robust variable geometries for advanced non-traditional geometries such as the turbine and diffuser
- The project also includes multi-disciplinary simulations including fluid flow, stress, and fatigue
- Future work will include additional components such as the 2nd stage axial turbine
- Extensive optimization studies of all components will be undertaken



Siemens Industrial Gas Turbines

- Parameterization of several components
- Automated workflows for optimization



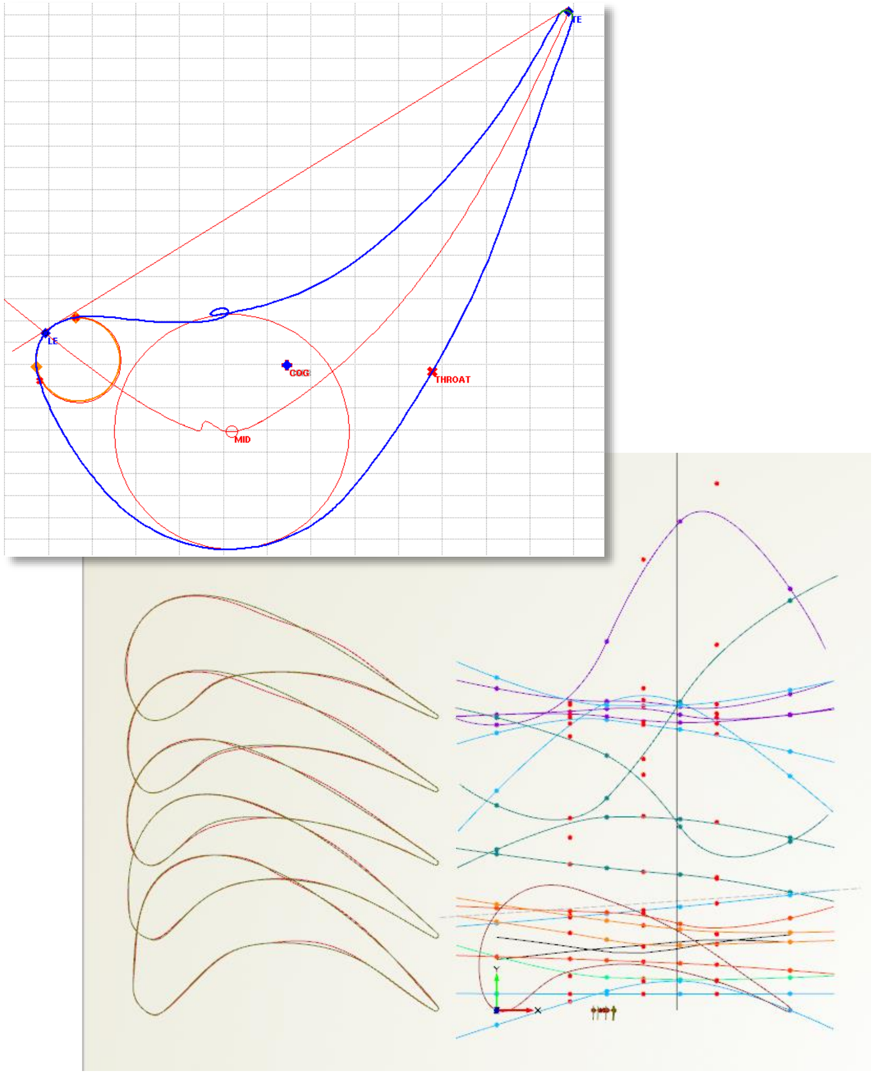
- Transition ducts

- Turbine blades
- Endwall contouring
- Squealer tips
- Film cooling

SIEMENS

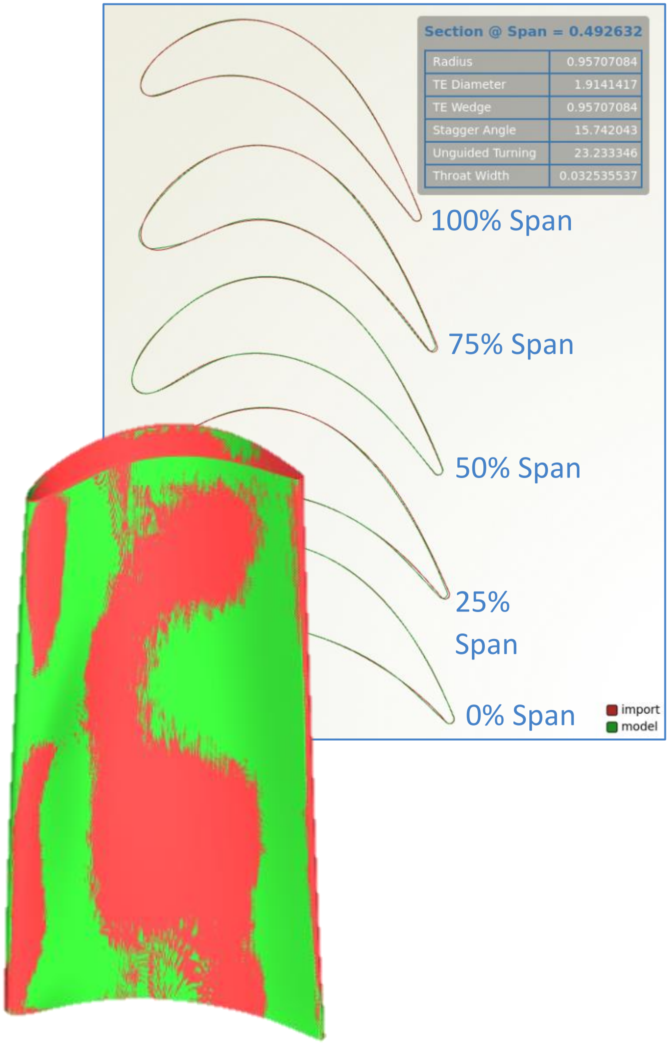
Flowpath aerodynamic optimization overview

- Motivation to use CAESES
  - Difficulties with in-house tools for high camber, high thickness airfoils
  - Minimize manual rework of airfoil geometries
- Siemens initiated the project with CAESES in 2015 to develop parametric airfoil models used for performance optimizations:
  - Automated fitting routine
  - Manual design of airfoils with CAESES
  - Exploration of parametric design space
  - Non-axisymmetric endwall contouring
  - Throat-area calculation and automated global restaggering



Automated fitting of airfoils

- Design often based on existing blade geometries
- Prior to any optimization routine, simplified parametric model must be generated
- CAESES automates the generation of the reduced-parameter model by fitting model to a specified baseline geometry
- Number of span-wise control points flexible and defined by user
- User is able to overlay the parametric model (green profiles) over the initial imported geometry (red profiles)
- Robustness of auto-fitting routine provides flexibility to parameterize wide range of turbine airfoil geometries
- User can manually fine-tune profile sections and/or stagger with the simplified parametric model
- 3D effects can easily be added through variations to the stacking line (pitchwise and axial – bow/sweep/shift)



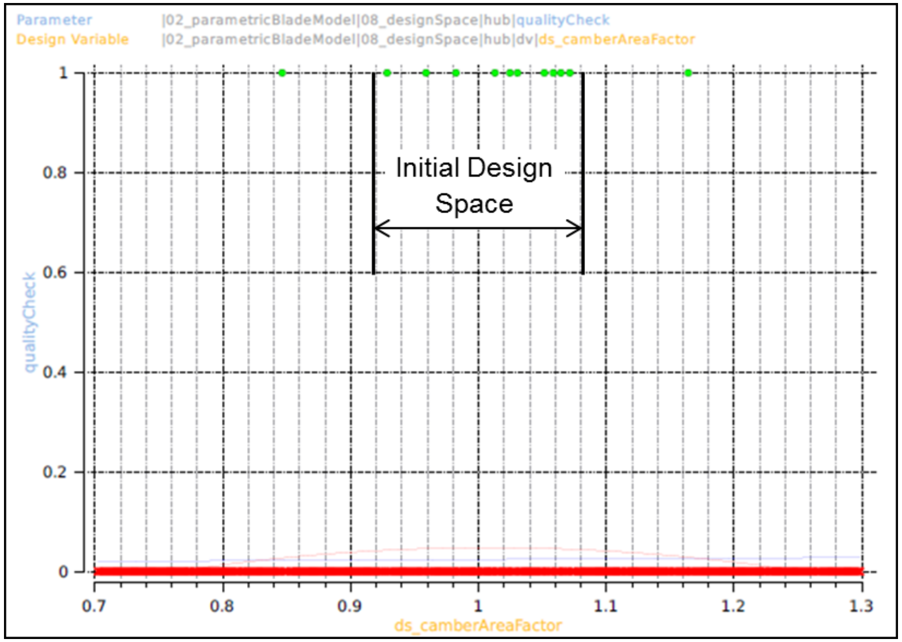
Section @ Span = 0.492632

Radius	0.95707084
TE Diameter	1.9141417
TE Wedge	0.95707084
Stagger Angle	15.742043
Unguided Turning	23.233346
Throat Width	0.032535537

SIEMENS

Design space exploration

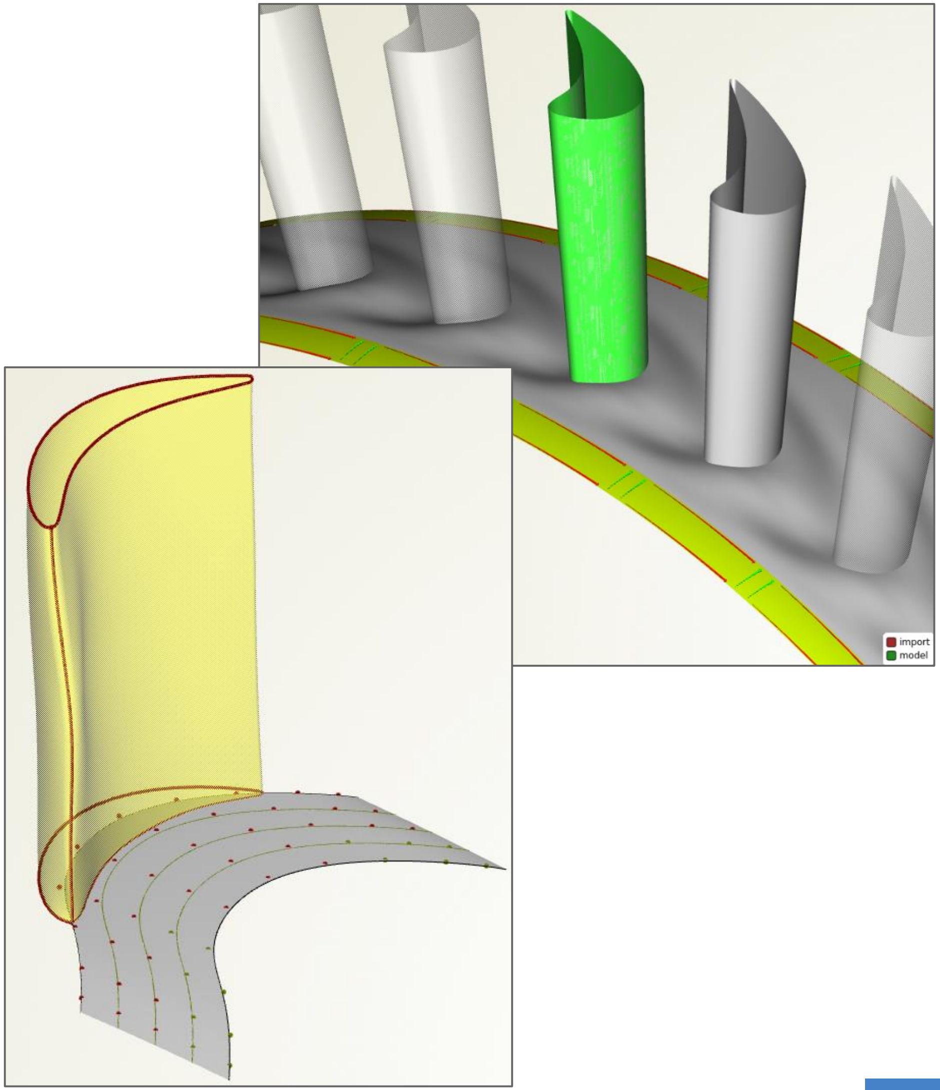
- Design Space Exploration feature allows user to explore the valid design space by running a DoE inside of CAESES
- Run hundreds of potential parameter combinations in a matter of minutes
- “Validity” criteria based on curvature and inflection points
- Automated PDF output shows general range for each parameter which produced “valid” designs
- Streamlines setup of the initial design space allowed in aerodynamic optimizations



SIEMENS

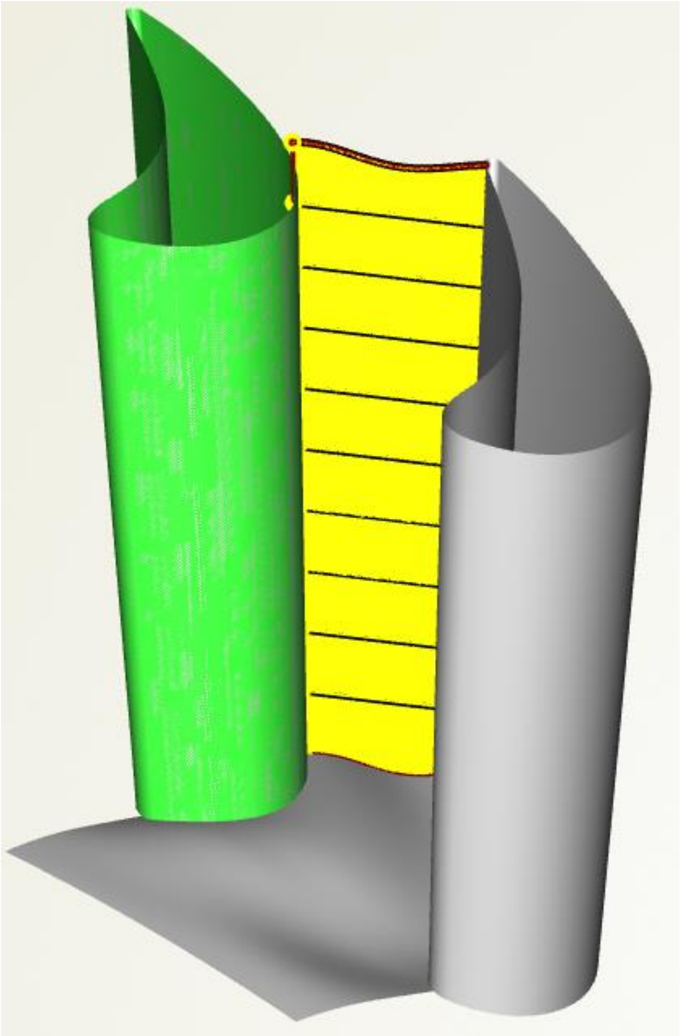
Endwall contouring

- Non-axisymmetric endwalls can be shaped in a multitude of ways, which often leads to a high number of parameters
- Balance between flexibility and optimization efficiency
- Arbitrary parameterization approaches can be used to define endwall contouring in CAESES, e.g.
  - Based on discrete number of control points
  - Based on trigonometric cross-section
  - Based on spline cross-section
  - …



Throat area correction

- In turbine airfoil design, throat area is a key geometric parameter to consider
- Parameterized blade model includes routine to calculate throat area of the 3D airfoil geometry (assuming airfoil pitch known)
- In cases of endwall contouring, throat area adjusted to contour
- Automated restagger feature globally rotates airfoils to match a specified throat area
- Important for optimizations where throat area changes are significant



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Flowpath aero optimization – tool chain

1. Geometry generation

CAESES

2. Mesh generation

NUMECA INGENIEURBÜRO

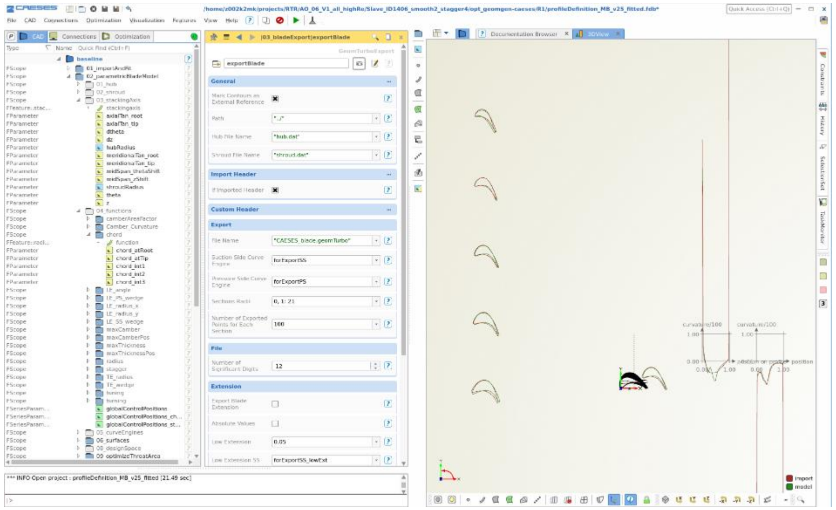
3. CFD simulation

ANSYS CFX

TRACE

Airfoil parameterization:

- Automated fitting of initial geometry
- ~ 5 radial sections
- ~ 20 parameters for stacking axis, stagger
- ~ 80 parameters to describe airfoil



- Export geomTurbo and endwall data

SIEMENS

Flowpath aero optimization – tool chain

1. Geometry generation

CAESES

2. Mesh generation

NUMECA INGENIEURBÜRO

3. CFD simulation

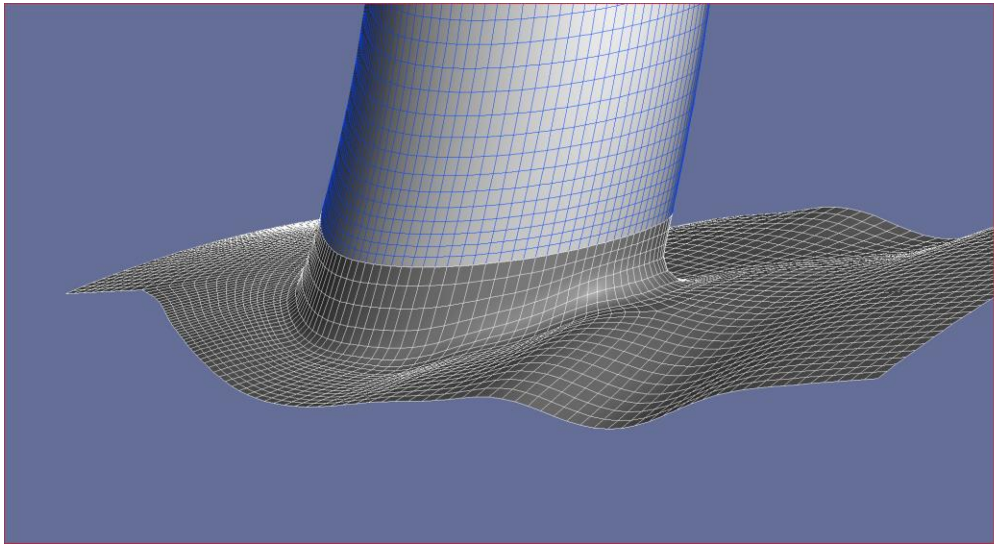
ANSYS CFX

TRACE

SIEMENS

Autogrid meshing strategy:

- High Re / low Re mesh including fillets, hub cavities and shrouds
- > 1M cells per row
- Butterfly O-mesh in fillets allow for non-axisymmetric endwalls

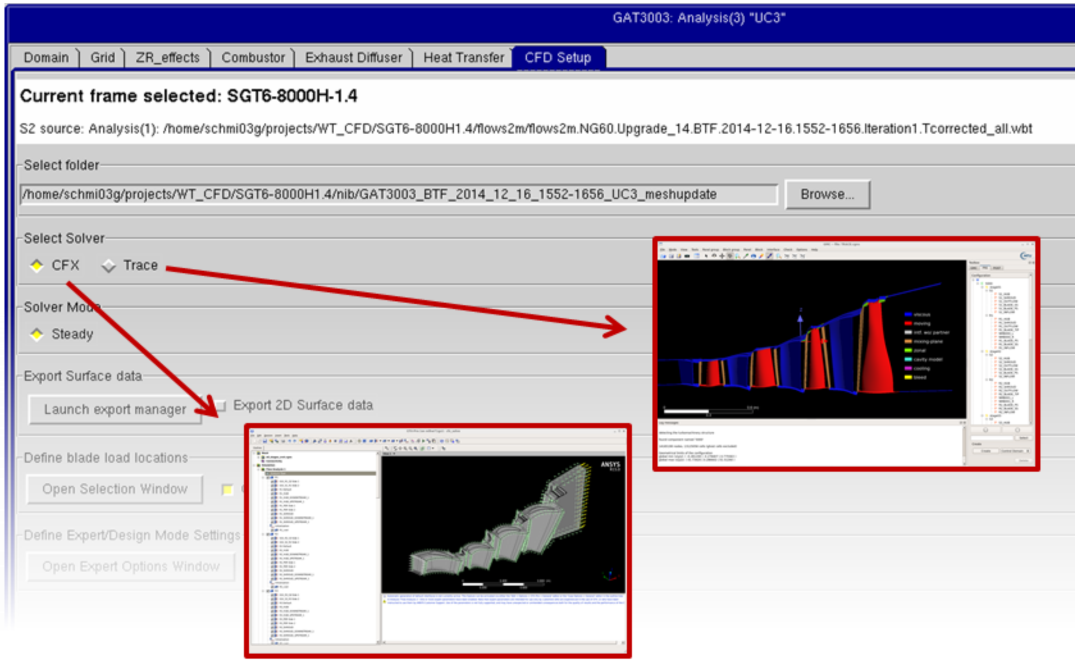


Flowpath aero optimization – tool chain

1. Geometry generation
2. Mesh generation
3. CFD simulation

CFX / TRACE:

- Steady state mixing plane
- SST turbulence model



Current frame selected: SGT6-8000H-1.4

S2 source: Analysis(1): /home/schmi03g/projects/WT_CFD/SGT6-8000H1.4/flows2m/flows2m.NG60.Upgrade_14.BTF.2014-12-16.1552-1656.Iteration1.Tcorrected_all.wbt

Select folder: /home/schmi03g/projects/WT_CFD/SGT6-8000H1.4/nib/GAT3003_BTF_2014_12_16_1552-1656_UC3_meshupdate

Select Solver: ◆ CFX ◇ Trace

Solver Mode: ◆ Steady

Export Surface data: ☐ Export 2D Surface data

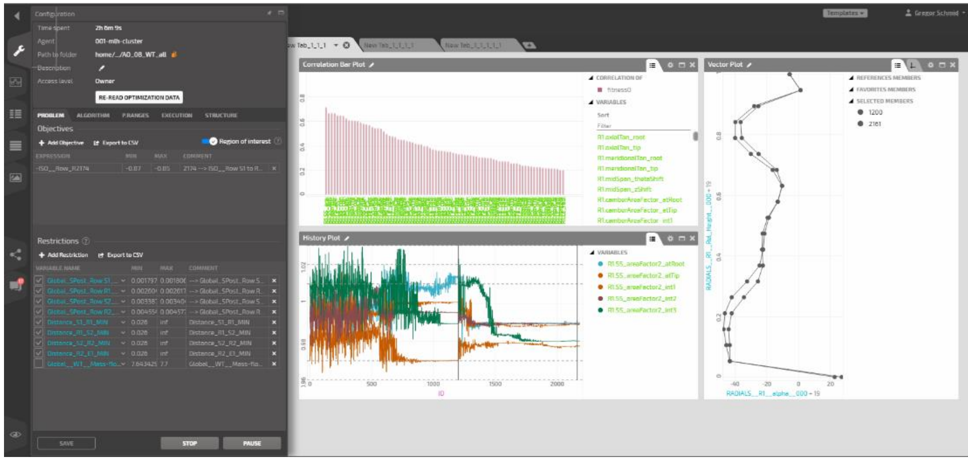
Define blade load locations

Define Expert/Design Mode Settings

SIEMENS

Flowpath aero optimization – tool chain

- Input Files:
  - Process chain
  - Optimization parameters
  - Optimization settings
- Bunch of scripts available:
  - Clean up, generate, modify members ...
  - Analyse process chain, write out data and plots ...
- Interactive, web-based control of optimization:
  - Generate plots and post-process data
  - Edit parameter limits, constraints



Configuration

Time spent: 2h 6m 9s
Agent: 001-mlh-cluster
Path to folder: home/.../AO_08_WT_all
Description
Access level: Owner

RE-READ OPTIMIZATION DATA

PROBLEM · ALGORITHM · P.RANGES · EXECUTION · STRUCTURE

Objectives

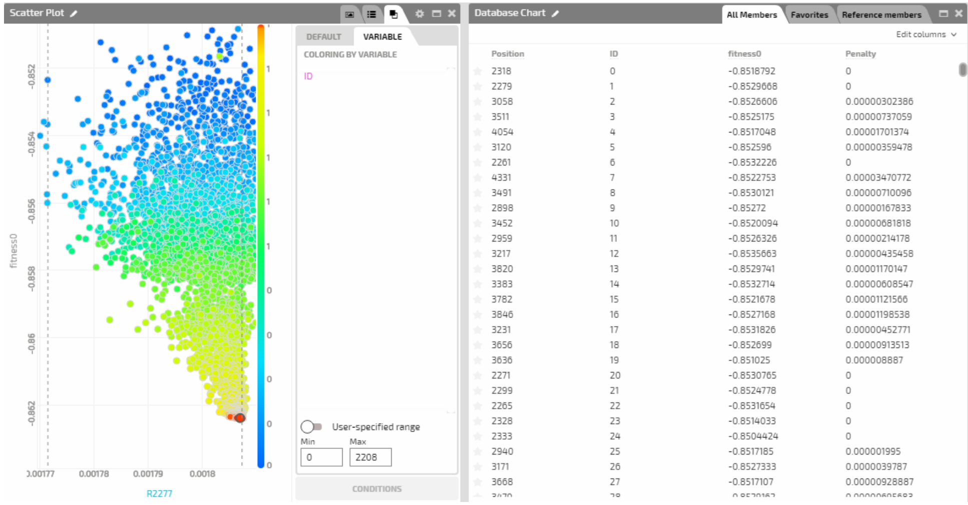
+ Add Objective · Export to CSV · Region of interest

EXPRESSION	MIN	MAX	COMMENT
-ISO__Row_R2174	-0.87	-0.85	2174 --> ISO__Row S1 to R...

Restrictions

+ Add Restriction · Export to CSV

	VARIABLE NAME	MIN	MAX	COMMENT
☑	Global_SPost_Row S1...	0.001797	0.00180	--> Global_SPost_Row S...
☑	Global_SPost_Row R1...	0.00260	0.002617	--> Global_SPost_Row R...
☑	Global_SPost_Row S2...	0.00338	0.00340	--> Global_SPost_Row S...
☑	Global_SPost_Row R2...	0.00455	0.00457	--> Global_SPost_Row R...
☑	Distance_S1_R1_MIN	0.028	inf	Distance_S1_R1_MIN
☑	Distance_R1_S2_MIN	0.028	inf	Distance_R1_S2_MIN
☑	Distance_S2_R2_MIN	0.028	inf	Distance_S2_R2_MIN
☑	Distance_R2_E1_MIN	0.028	inf	Distance_R2_E1_MIN
☐	Global__WT__Mass-flo...	7.643425	7.7	Global__WT__Mass-flo...



User-specified range: Min 0, Max 2208

Database Chart

All Members · Favorites · Reference members

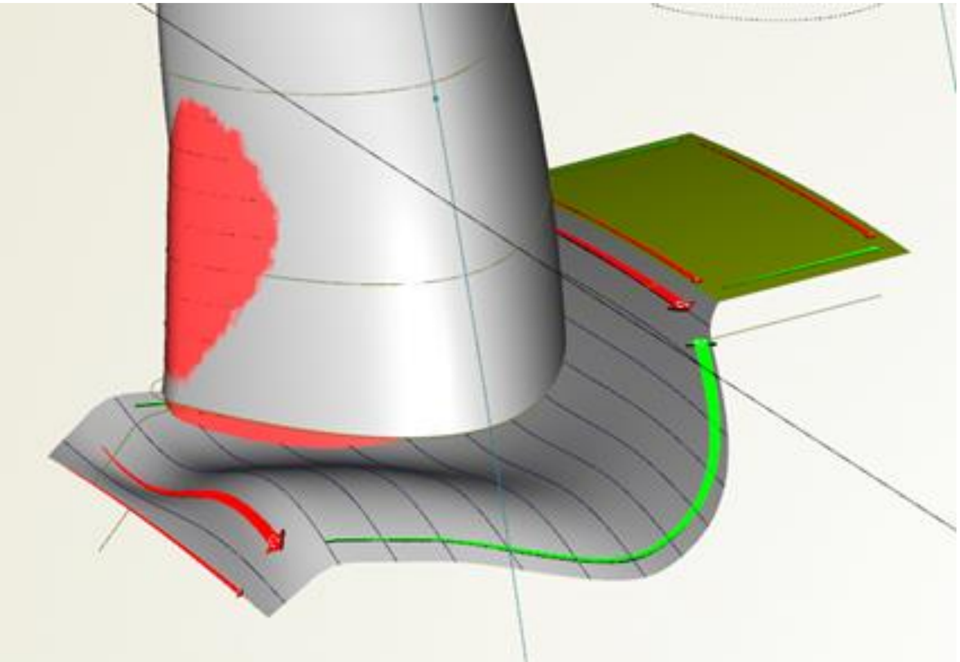
Edit columns

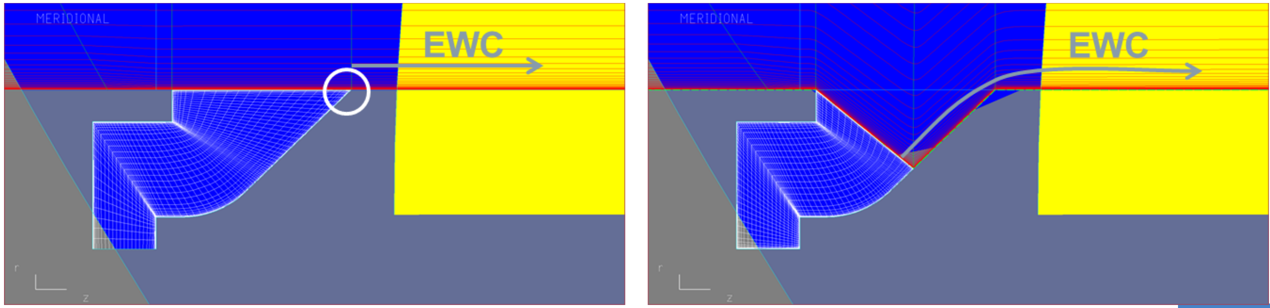
Position	ID	fitness0	Penalty
2318	0	-0.8518792	0
2279	1	-0.8529668	0
3058	2	-0.8526606	0.00000302386
3511	3	-0.8525175	0.00000737059
4054	4	-0.8517048	0.00001701374
3120	5	-0.852596	0.00000359478
2261	6	-0.8532226	0
4331	7	-0.8522753	0.00003470772
3491	8	-0.8530121	0.00000710096
2898	9	-0.85272	0.00000167833
3452	10	-0.8520094	0.00000681818
2959	11	-0.8526326	0.00000214178
3217	12	-0.8535663	0.00000435458
3820	13	-0.8529741	0.00001170147
3383	14	-0.8532714	0.00000608547
3782	15	-0.8521678	0.00001121566
3846	16	-0.8527168	0.00001198538
3231	17	-0.8531826	0.00000452771
3656	18	-0.852699	0.00000913513
3636	19	-0.851025	0.000008887
2271	20	-0.8530765	0
2299	21	-0.8524778	0
2265	22	-0.8531654	0
2328	23	-0.8514033	0
2333	24	-0.8504424	0
2940	25	-0.8517185	0.000001995
3171	26	-0.8527333	0.0000039787
3668	27	-0.8517107	0.00000928887

Flowpath aero optimization – Ex.1: 1.5 stage turbine rig

- Reduce blade count by 20%
- Introduce non-axisymmetric endwall (EWC) and advanced blade tips
- 3D optimization with 89 parameters in total based on TRACE
- Optimization of blade1 leads to 0.9 ppts improvement
- Including EWC gave another 0.3 ppts

→ <u>1st stage improves by +0.2/0.3 ppts steady/transient (experiment +0.3 ppts)</u>

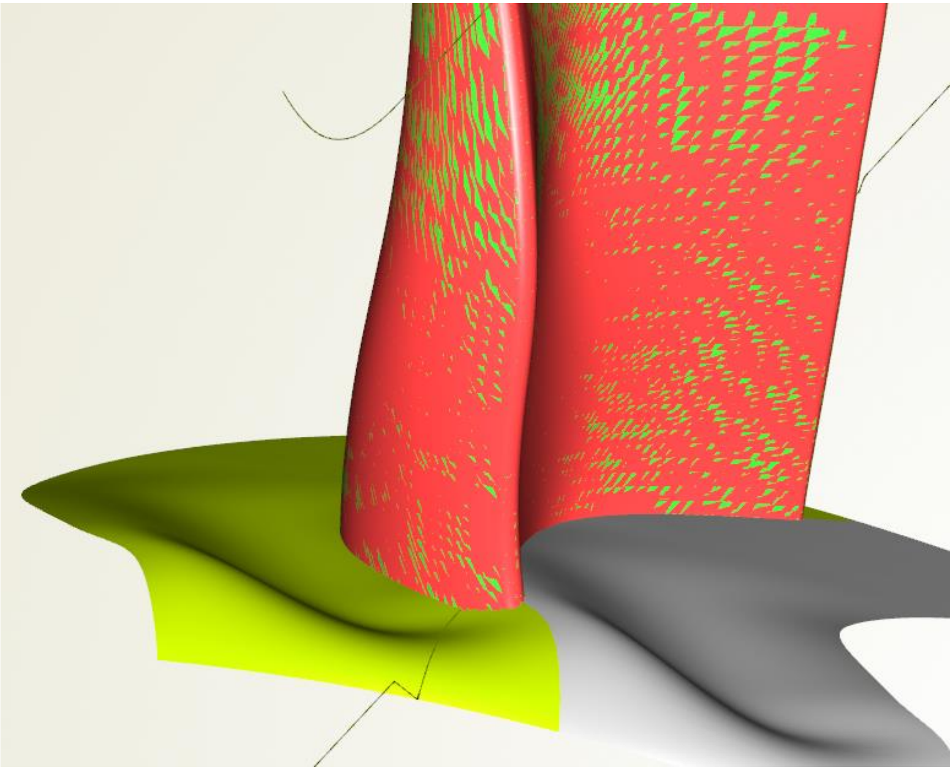




Flowpath aero optimization – Ex.2: 2.5 stage turbine rig

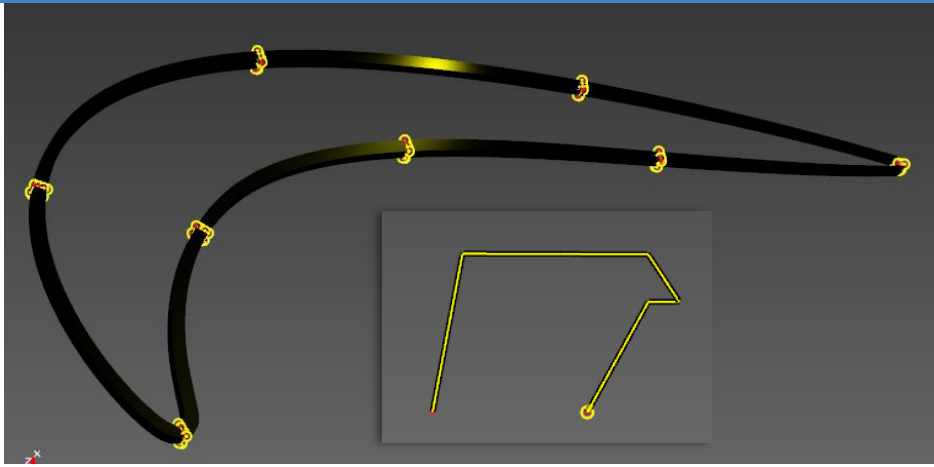
- Significant increase of blade loading by count/chord reduction
- Airfoil optimization with ~100 parameters per blade row
- Endwall optimization with 8 parameters per surface

→ Performance improves 0.7 ppts over baseline

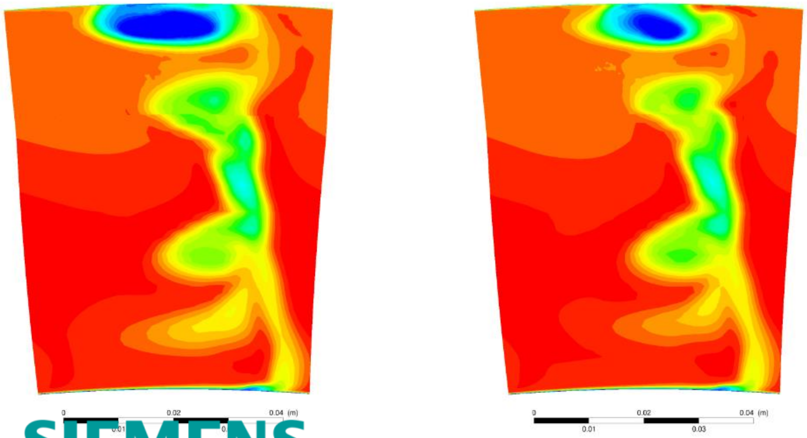


Blade tip optimization – squealer tip

- Blade tip squealer cavity
  - Parametric cross section of squealer fence at several locations
  - Include cutout at any arbitrary location
  - 1.5-stage CFD setup in STAR-CCM+



- 1.5 stage efficiency improved by 0.6% over baseline squealer tip



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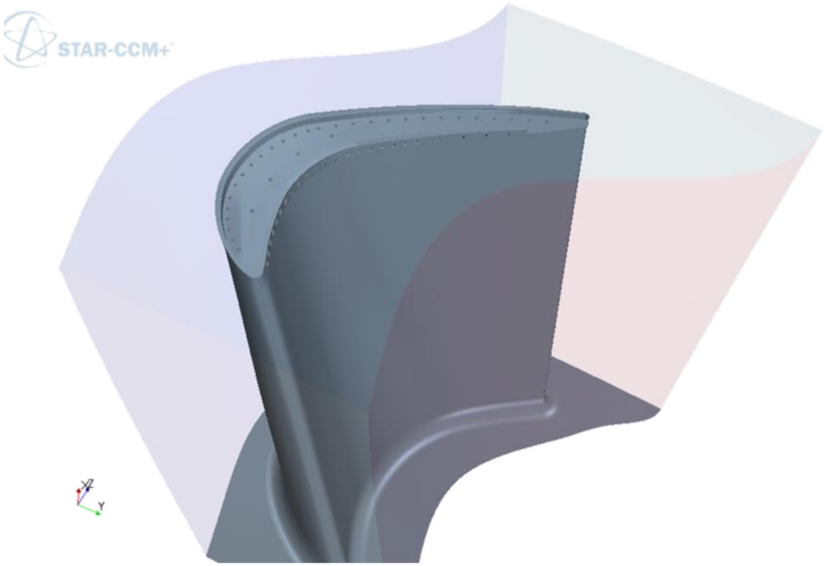
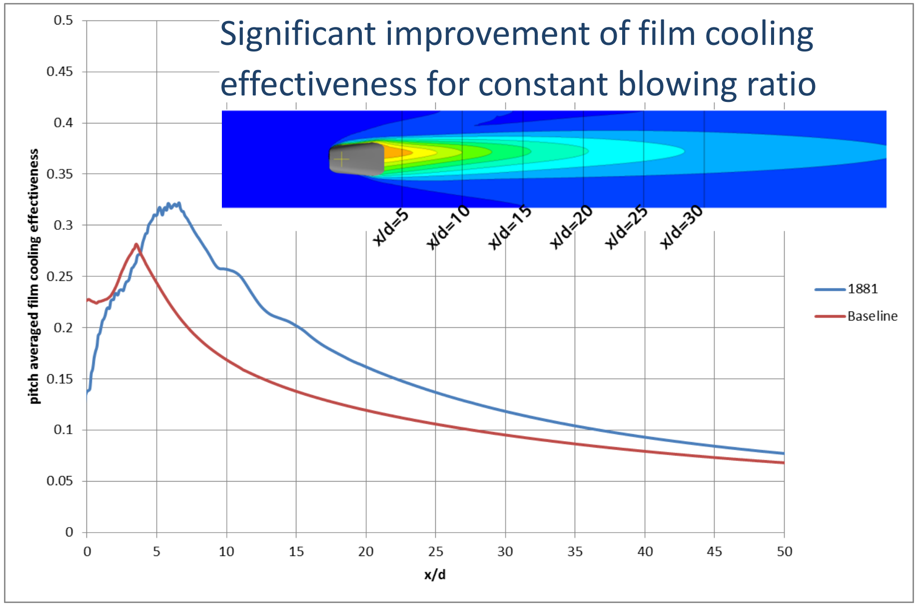
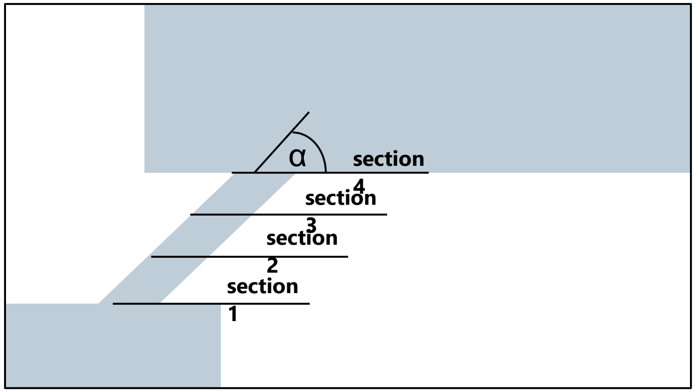


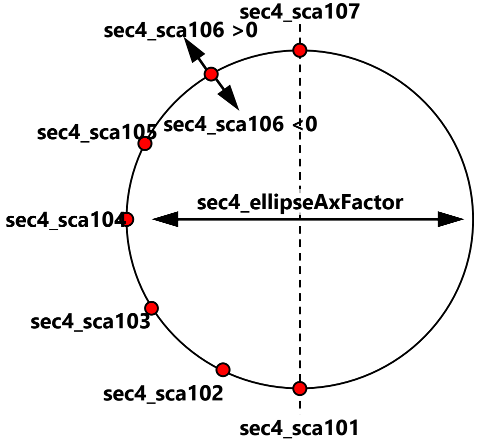
Film cooling hole optimization – diffuser geometry

- Parameterization
  - 4 sections
  - 7 control points per section
  - 2 angles, aspect ratio, eccentricity
- Tool chain
  - Geometry variants
  - Mesh generation
  - CFD simulation

CFX


Significant improvement of film cooling effectiveness for constant blowing ratio





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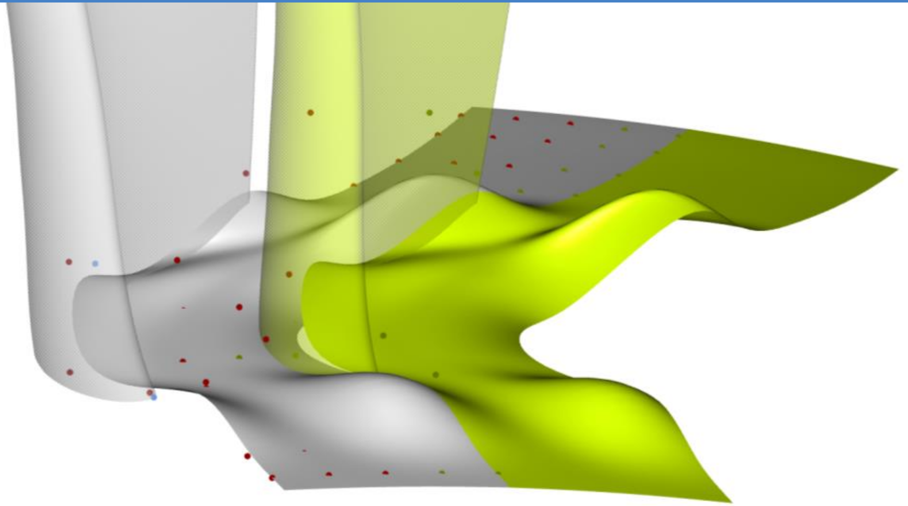
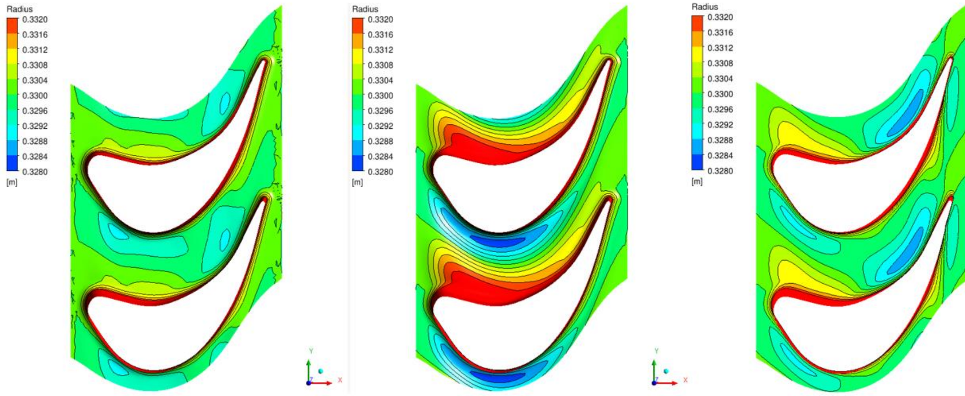
Aero optimizations based on CAESES

Conclusion:

- Turbine airfoil and endwall parametrization is widely based on CAESES for production design at Siemens
- Additional functionality as automated fitting, exploration of design space and others successfully implemented in standard work flow
- Customized implementation allows CAESES to be used by non-experts
- CAESES has found its way into several applications besides the main flow path design, e.g. blade tips, cooling holes, …

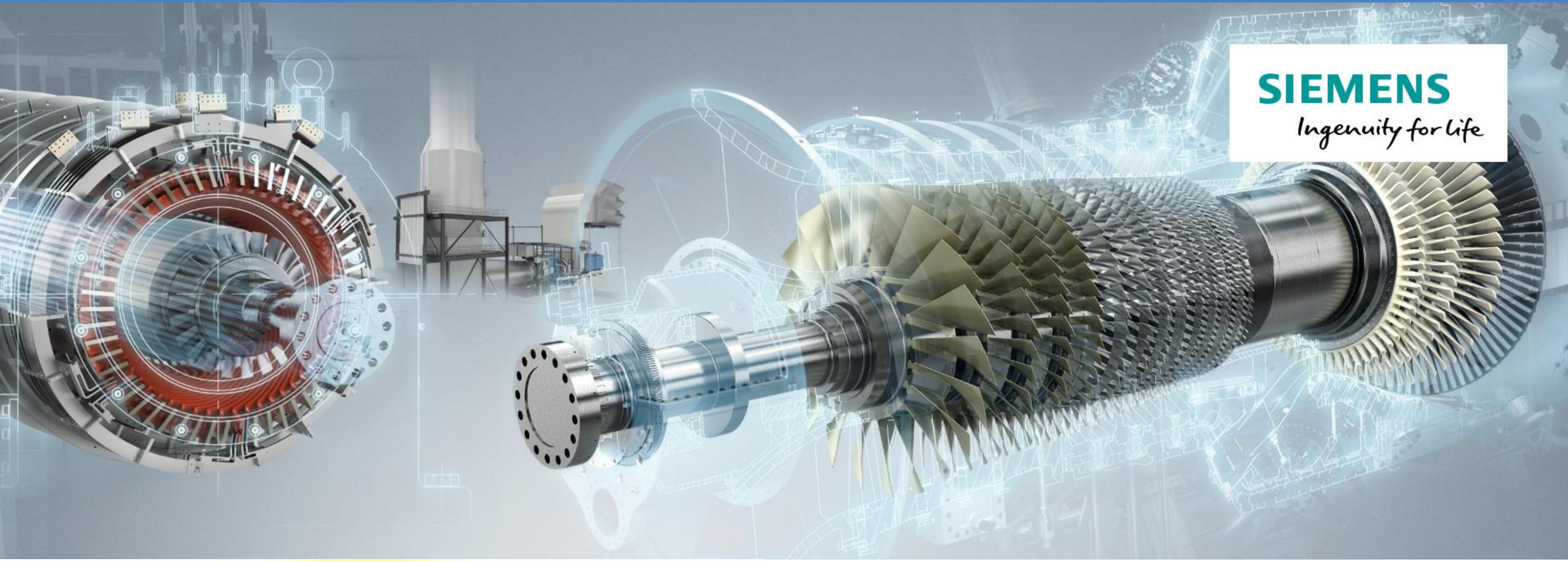


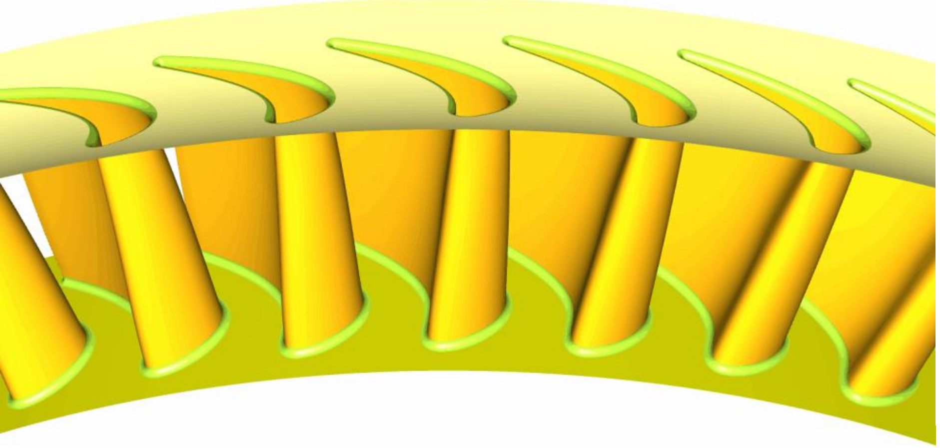


Outlook:

- Combine CFD with FEA for thermal and stress analysis within the optimization process (MDO)
- Next project is to parameterize the airfoil internal cooling passages

Aerodynamic optimizations based on CAESES





We launched a pilot project with FRIENDSHIP SYSTEMS to evaluate CAESES in May, it helped us solve a time-critical task in July and it became a design tool by October. By then we had created flexible and robust parametric models for complex parts, enabling us to optimize in design spaces we had previously not been able to explore.

Tilman auf dem Kampe

Head of Aerodynamics Technology Development
Large Gas Turbine Engineering - SIEMENS

The End! Thanks for your attention!

CAESES, Your Upfront CAE System for Shape Optimization

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