

Heavy Duty 126 MW GT upgrade for aerodynamic performance improvement



Authors: Roman Kochurov, PhD – SoftInWay Inc. – Burlington, USA

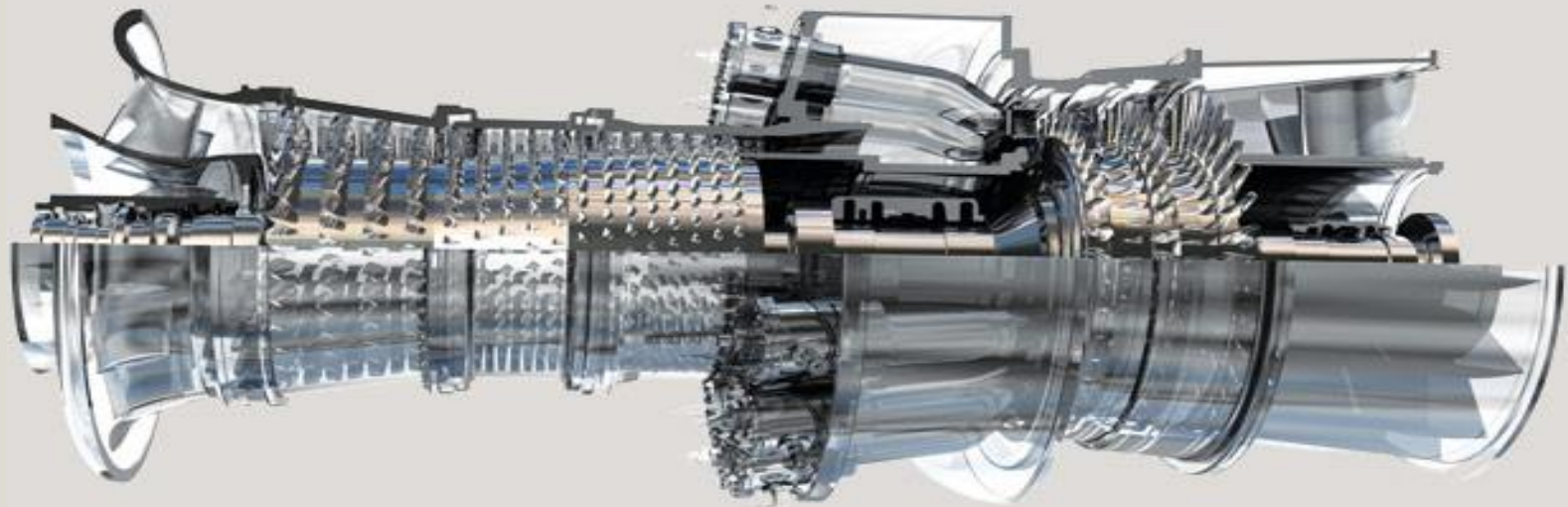
r.kochurov@softinway.com

Massimiliano Malvassora – SoftInWay Switzerland – Zug, Switzerland

max.malvassora@softinway.com

Turbine Services LTD – Saratoga NY, USA

Sales@turbineservices.com



Presentation Agenda



Introduction

Scope of the project

Turbine Modelling & Aero Performance Analysis

Airfoil Optimization and CFD Validation

Blade and Nozzle mechanical design

Coupled Aero-Thermal CFD Analysis

Mechanical Integrity and Reliability

Conclusions

Capabilities & Reach



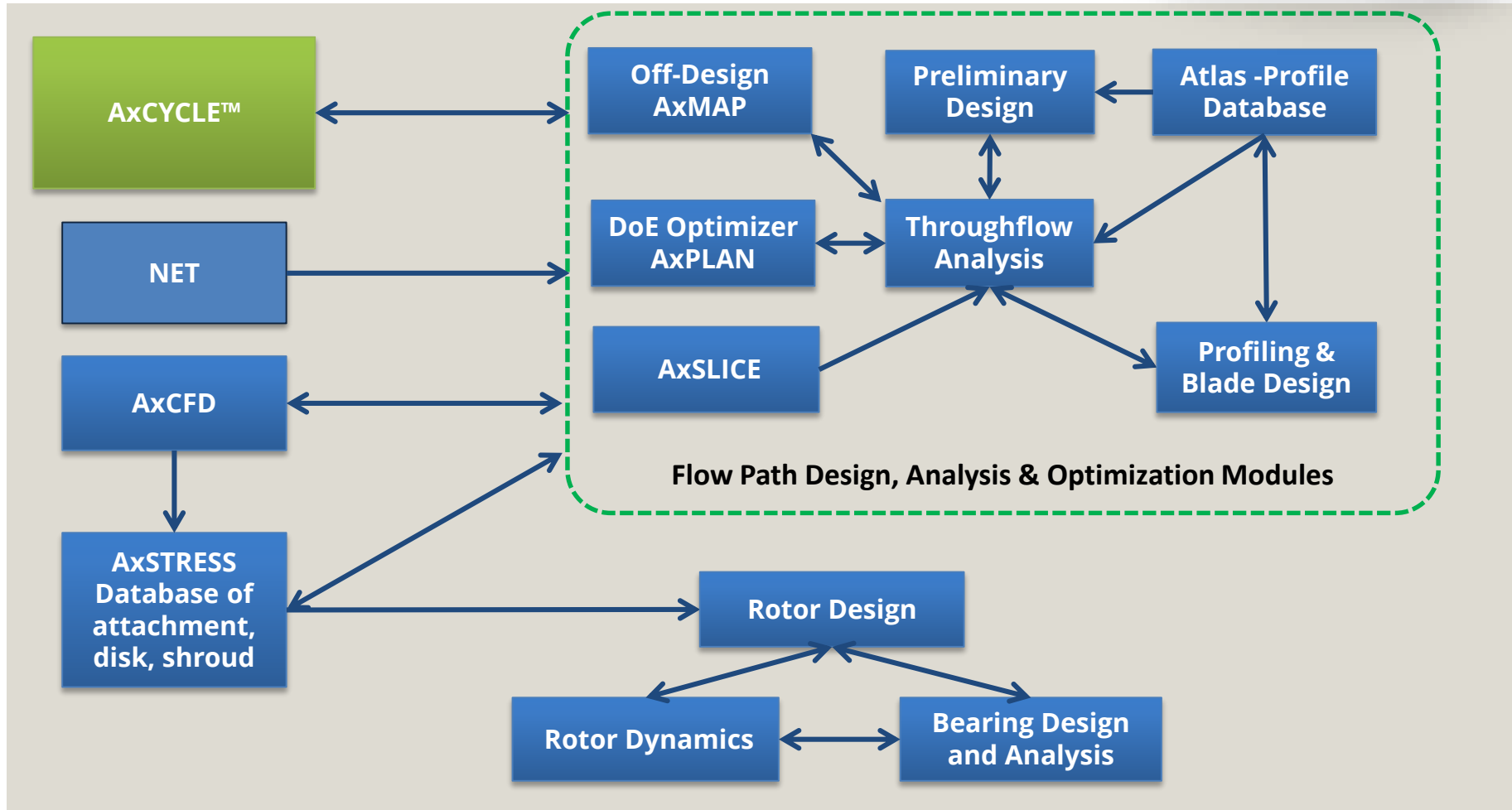
AxSTREAM - Platform for Turbomachinery Design, Analysis and Optimization, as well as Thermal Conversion Cycle Design, Optimization and Costing

Engineering Services
New Product Development

Education and Training Services
SoftInWay Turbomachinery University

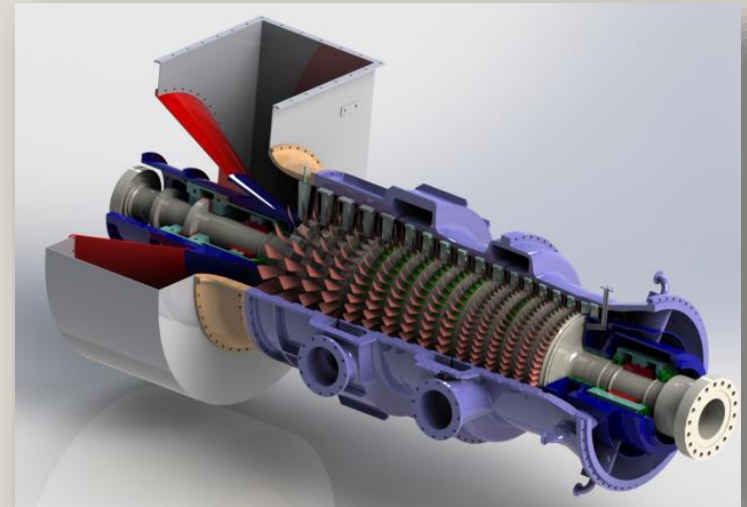


AxSTREAM Software Platform





- Project Definition and Technical Specifications
- Research & Development to Support New Designs
- Preliminary Design & Feasibility Studies
- Analysis of Existing Machine
- Turbomachinery Retrofitting & Upgrades
- FEA/CFD Analysis
- Heat Transfer Simulations
- Rotor Dynamics
- Mechanical Design of Components
- Complete Design Process



**More than 120 consulting projects since inception
for Industry and Research Organizations**



Turbine Services, Ltd.

- Over 40 Years of Manufacturing Excellence
- Specialize in the Design and Manufacturing of Spare Parts
- Largest Non-OEM Replacement Gas Turbine Parts Manufacturer
 - Seven Product Lines Flange-to-Flange
- Stamp of Approval from OEM's Manufacturing Associates
- Active in 120 Countries Worldwide

TSL Engineering Capabilities



Turbine Services, Ltd.

- Engineering Reinforced by Industry Leading Quality Assurance Program
- Industry leading Design Knowledge and Manufacturing Experience
- Reverse Engineering and Re-Engineering Specialist
- On-Site Design Verification and Validation
- Industry Leading Product-To-Market Development Cycle



- ISO 9001:2008 Certified and Approved for Manufacturing and Design
- International Supply Chain Comprised of ISO-Certified Manufacturers
- Strict Inspection Criteria to Maintain Rigorous Quality Standards
- Advanced Inspection Methods that Utilizing State-of-the-Art Equipment
- Continuous Process Improvements to Inspection and Quality programs
- Proprietary Inspection Equipment Backed by Third Party Inspections
- Consistently High Quality Standards Across All Product Lines

Scope of the Project



- Turbine Services Ltd. , a supplier of replacement parts for GE Large Frame Gas Turbines, has worked with SoftInWay's engineering team on the redesign of the third stage of the GE Frame 9E heavy duty gas turbine.
- The scope of this project included the redesign of the third stage vanes and blades to create components competitive with the GE Advanced Aero Uprate package.
- The redesign needed to meet the increased efficiency and structural integrity of the OEM's official upgraded parts, while avoiding the geometric limitations imposed by the US Patents held by GE.

GE-PG917E General Information



The Frame 9E heavy duty 50 Hz gas turbine is a single shaft machine with 3 stages in the turbine section.

Model	Ship Dates	ISO Performance* kW	Firing Temp °F/°C	Air Flow 10 ⁶ lbs/hr 10 ⁶ kg/hr	Heat Rate BTU/kWhr kJ/kWh	Exhaust Temp °F/°C
PG9113B	1975-81	86,200	1840/1004	2.736/1.241	10,990/11,592	945/507
PG9141E	1978-81	105,600	1955/1068	3.155/1.431	10,700/11,286	953/512
PG9157E	1981-83	109,300	1985/1085	3.183/1.444	10,700/11,286	968/520
PG9151E	1983-87	112,040	2000/1093	3.214/1.458	10,570/11,149	877/525
PG9161E	1988-91	116,930	2020/1104	3.222/1.461	10,290/10,854	980/527
PG9171E	1991 2003 - Current	123,450 126,100	2055/1124 2055/1124	3.231/1.466 3.231/1.466	10,080/10,632 10,100/10,650	998/537 1009/543
PG9231EC	1996	165,700	2200/1204	4.044/1.834	9,870/10,411	1,037/558
PG9301F	1993-94	209,740	2300/1260	4.804/2.179	10,080/10,632	1,082/583
PG9311FA	1994	223,760	2350/1288	4.819/2.186	9,630/10,158	1,097/582

Model: PG9171(E)

Frame 9 standard base load power output: 126,100kW
 Base load RPM: 3,000
 Compressor mass flow rate: 921 lb/s
 Compressor pressure ratio: 12.6
 First stage inlet temperature: 2055°F
 (Exhaust temperature: 1009°F)

Stage-3 Bucket & Nozzle (Advanced Aero)

GE has redesigned stage-3 bucket and stage-3 nozzle for the 6B, 7B-7EA, and 9B-E gas turbine classes to increase their efficiency and improve the output (up to +1%, at ISO cond.) and heat rate (up to -1% at ISO cond.).



Patent Protected GE Advanced Design*:



Scope of the Project:



The aero and mechanical requirements from Turbine Services Ltd. required the following steps:

- Nozzles and blades airfoil modifications, including twist and lean;
- Nozzles' and blades' profile optimization with minimized losses while avoiding infringement of GE patents;
- Performance analysis performed in AxSTREAM 2D solver with 3D CFD validation demonstrating performance figures competitive with GE advanced stage 3 design;
- Detailed 3D design of the newly developed nozzles blocks and blades with shroud and dovetail;
- Complete cycle of thermo-structural analyses for the air cooled Nozzle blocks and rotating Blades, in order to validate the advanced structural integrity in comparison to GE upgrade parts;
- Complete 3D CAD models development;

Project Steps



Step 1: GE Original and Advanced Flow path modeling and performance analysis - This was performed to understand the GE Advanced Design and the GE patented design features information on airfoil geometry.

Step 2: Redesign of stage 3 - SoftInWay optimized and created airfoil variants to avoid patent infringement. Their performance was studied in AxSTREAM and in CFD and vanes and blades airfoils were finalized to satisfy efficiency and preliminarily-defined structural criteria.

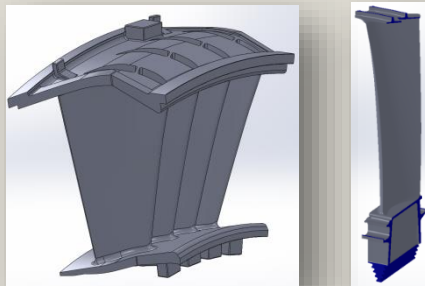
Step 3: Aerodynamic Comparison with GE Advanced Design – GE Advanced design and SoftInWay's variant were compared in CFD to analyze their efficiency and define the thermal boundary conditions and loads needed for the detailed structural analysis.

Step 4: Structural Comparison with GE Advanced Design – GE Advanced design and SoftInWay's variant were studied and compared with regards to structural capabilities based on Boundary Conditions from the 3D CFD study.

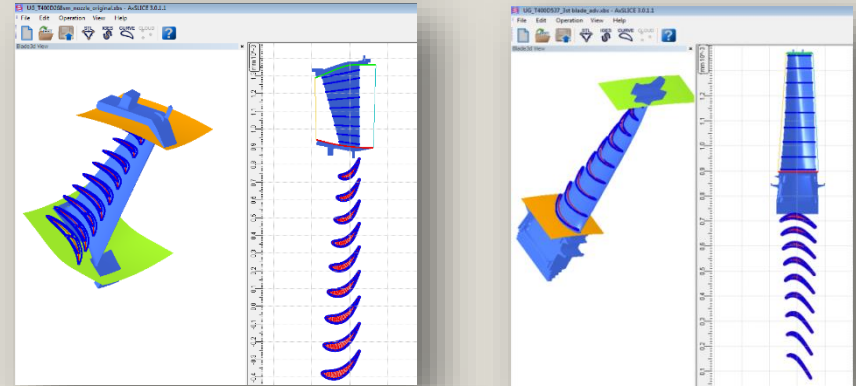
AxSTREAM GT flow path modelling



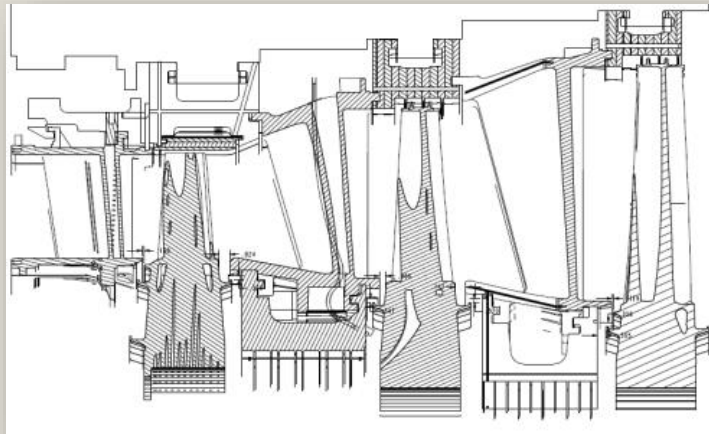
3D Solid Models from customer



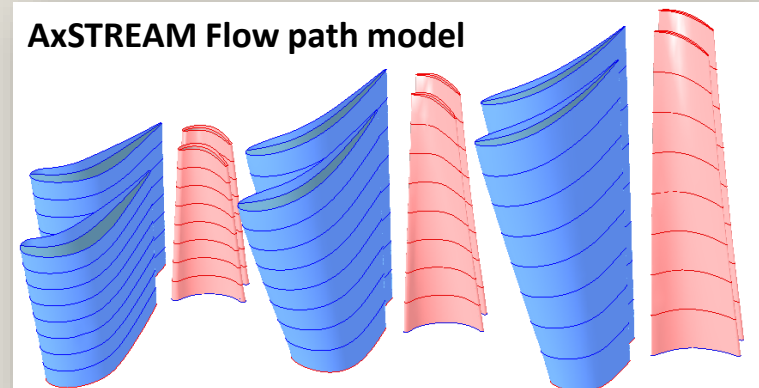
Extraction of nozzles and blades profiles through AxSLICE



Gas path assembly/drawings



AxSTREAM Flow path model

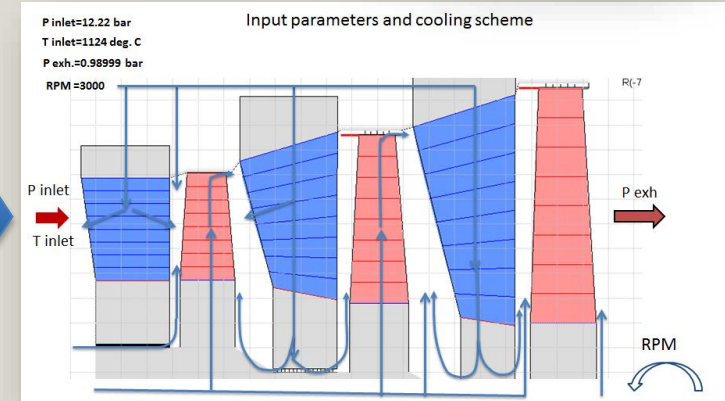


AxSTREAM Model - Operational parameters and cooling scheme

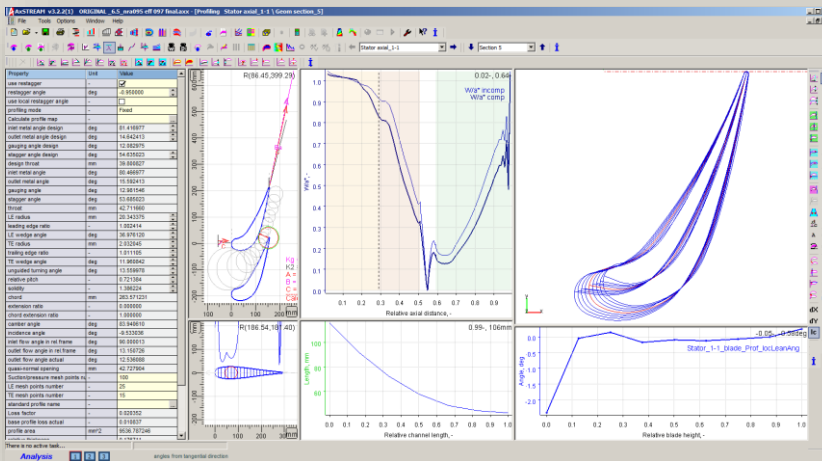


Cooling flows in % of Total cooling flow rate

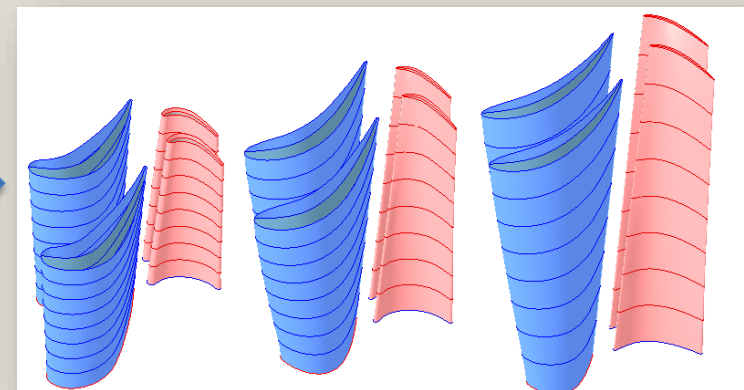
Cooling Flows as a % of Total cooling	Stator axial_1-1	Rotor axial_2-1	Stator axial_3-2	Rotor axial_4-2	Stator axial_5-3	Rotor axial_6-3
Tip Cooling						
LE Cooling						
TE Colling						
Hub Endwall Cooling						
Shroud Endwall cooling						



Profiles optimization and airfoil 3D staking



GT 3D model in AxSTREAM



Stage 1

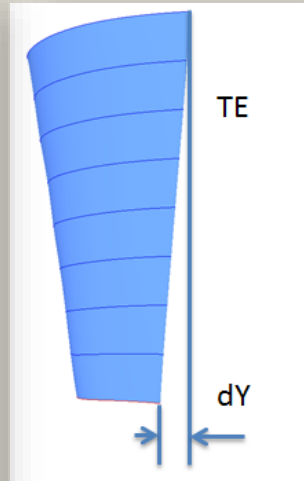
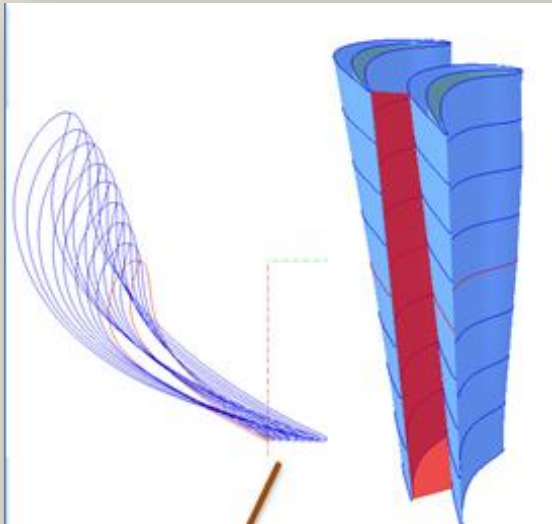
Stage 2

Stage 3

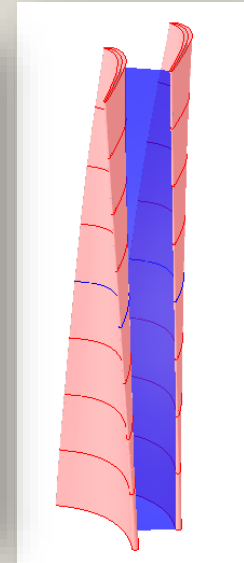
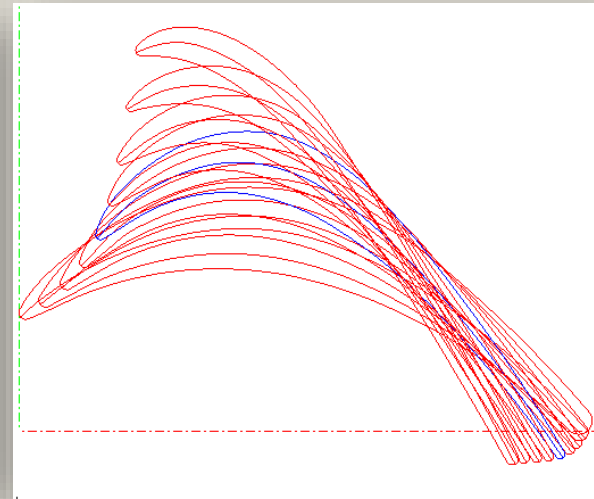
Stage 3 Nozzle and Blade AxSTREAM-optimized 3D design



Nozzle profiles with Twisted and Leaned airfoil



Blade profiles and 3D optimization

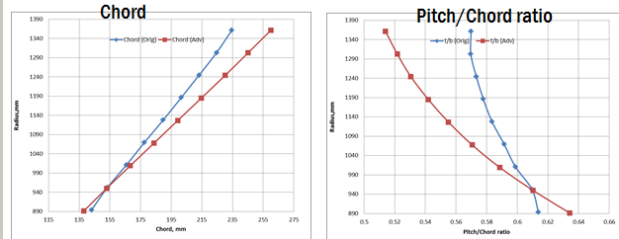
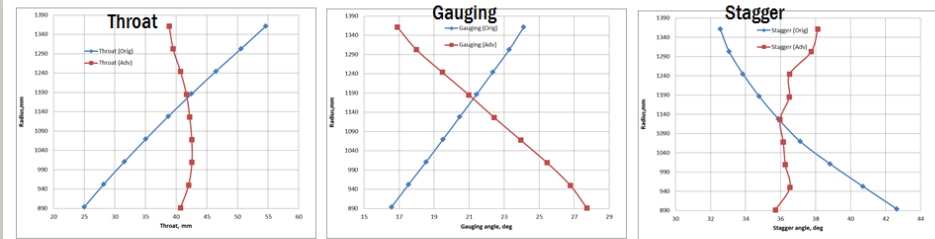


Stage 3 Nozzle and Blade AxSTREAM-optimized 3D design



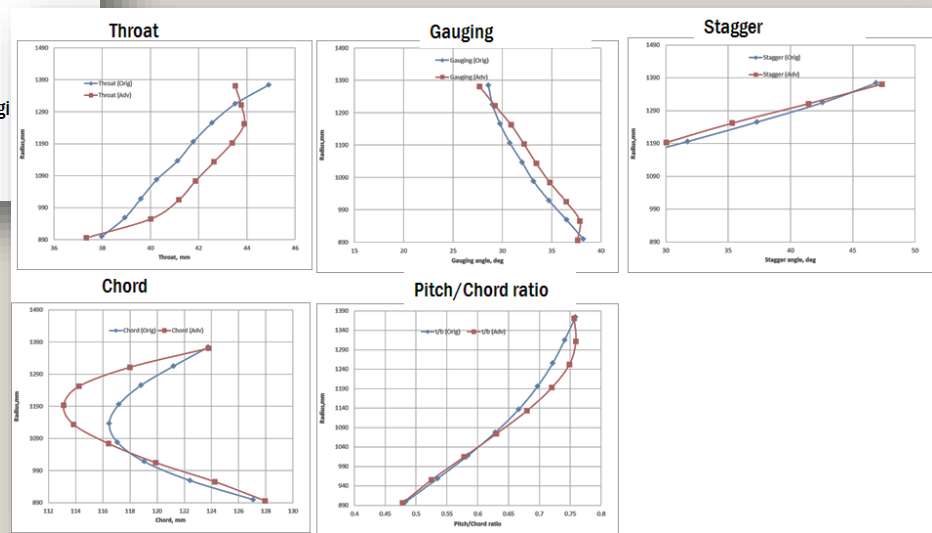
Radial parameters distribution

Optimized vs. Original Nozzles

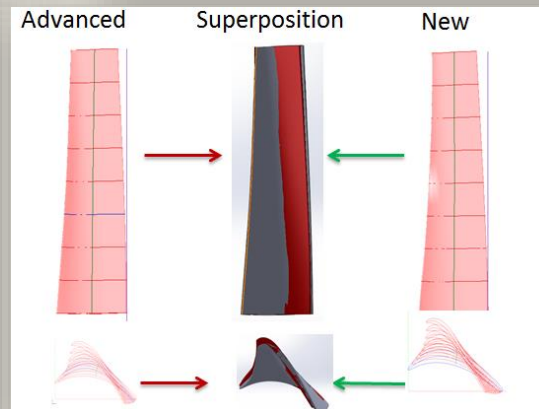
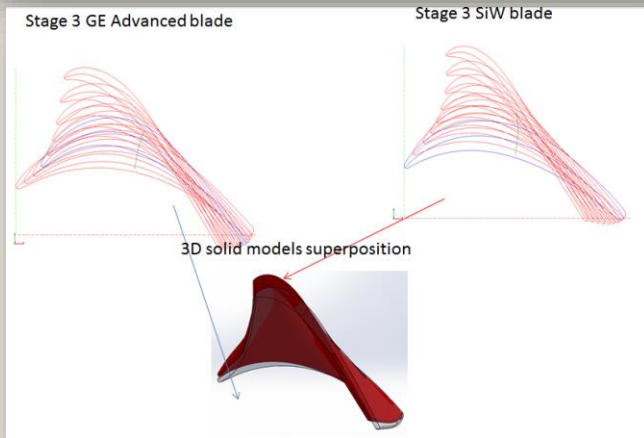
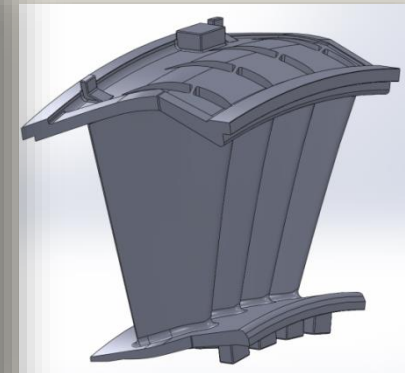
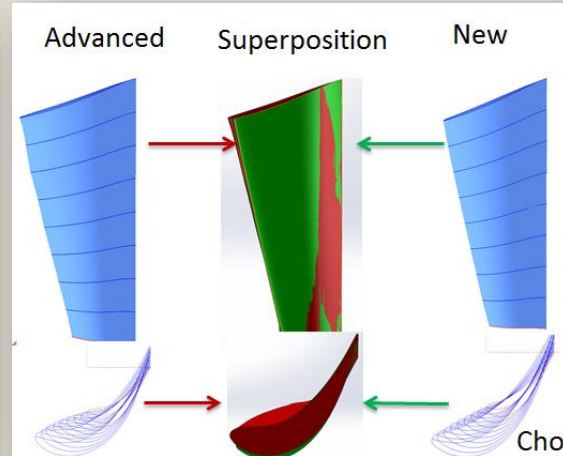
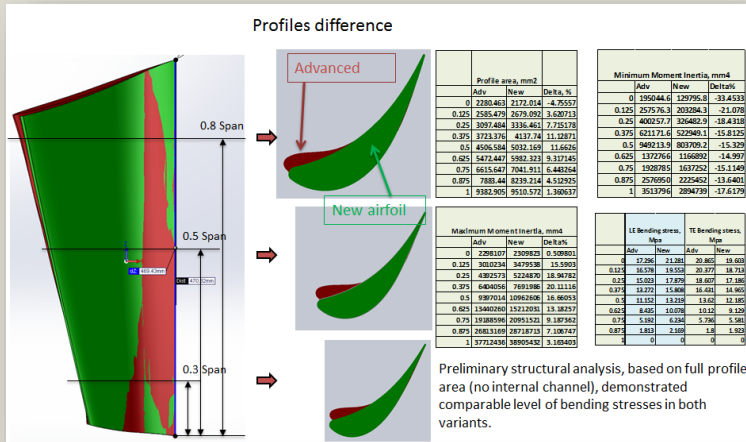


Original
Optimized

Proposed design features:
More total throat area
Nozzle twist to increase gauging angles at root
Tangential lean



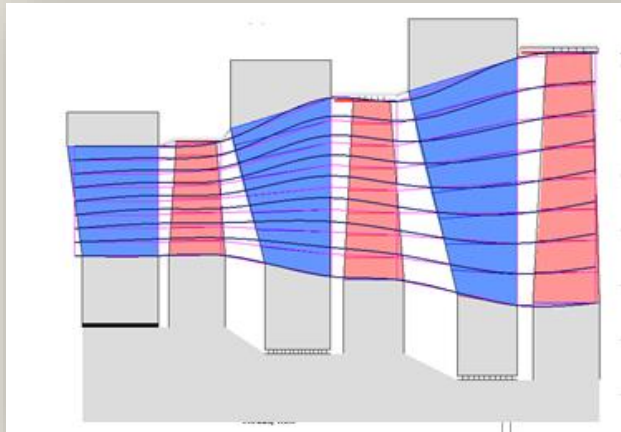
Stage 3 Nozzle and Blade AxSTREAM-optimized 3D design



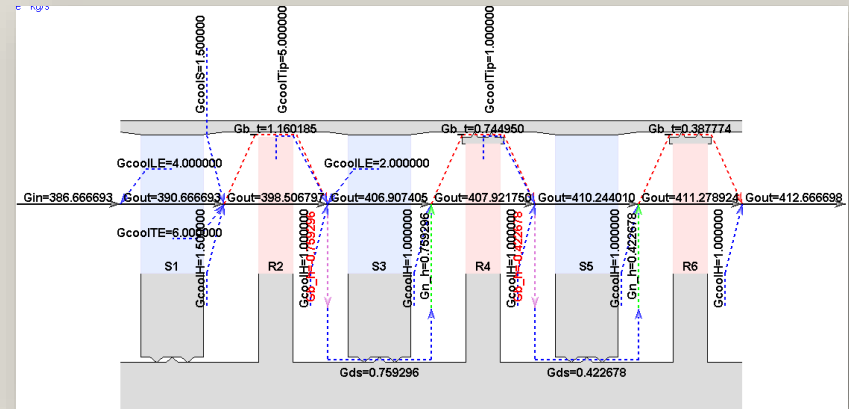
AxSTREAM - 2D AERO Performance analysis with Cooling



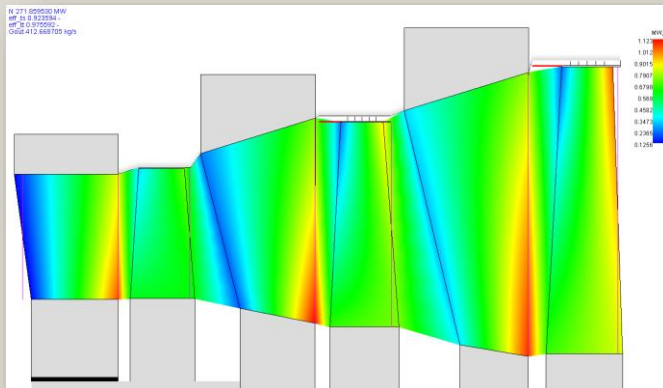
2D solver - streamlines



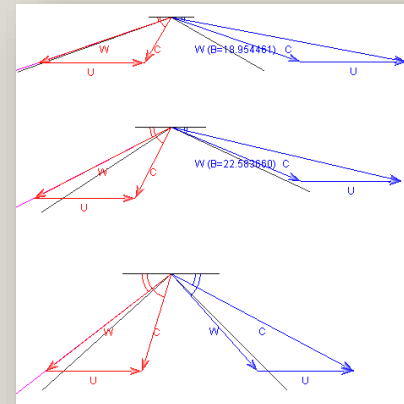
Flow diagram with leakages and cooling flows



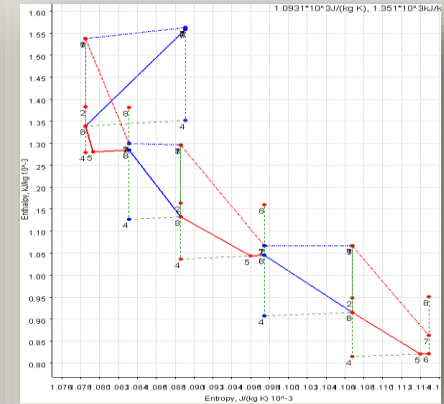
2D solver – Mach Number



Velocity triangles



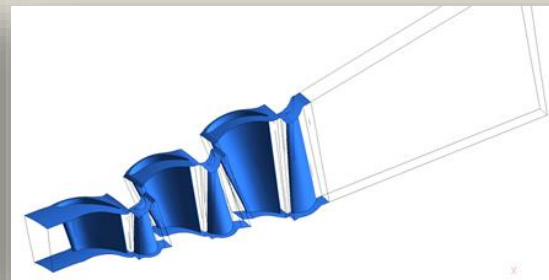
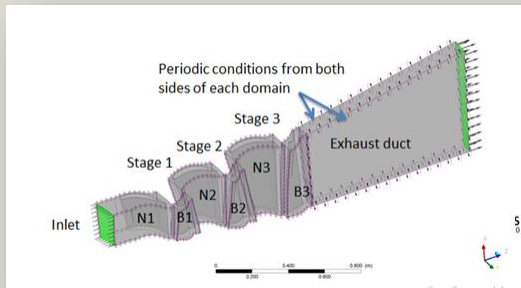
Mollier chart



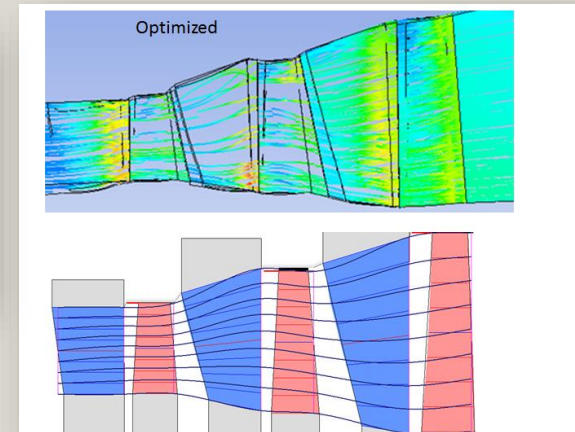
Aero performance validation in CFD



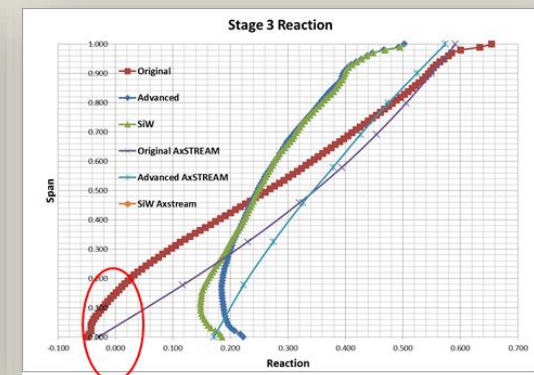
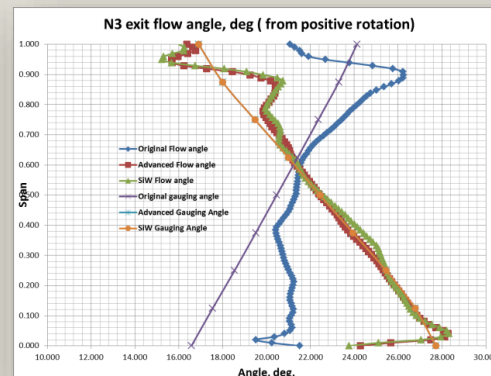
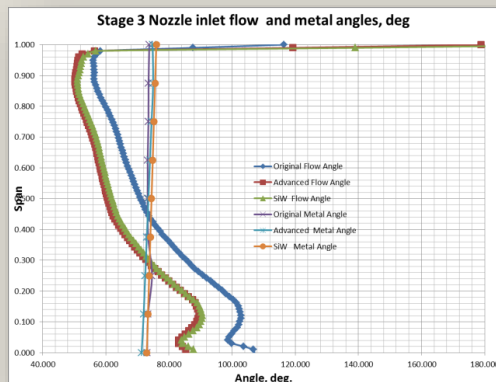
CFD model details



CFD vs. AxSTREAM streamlines comparison



Radial parameters distribution analysis

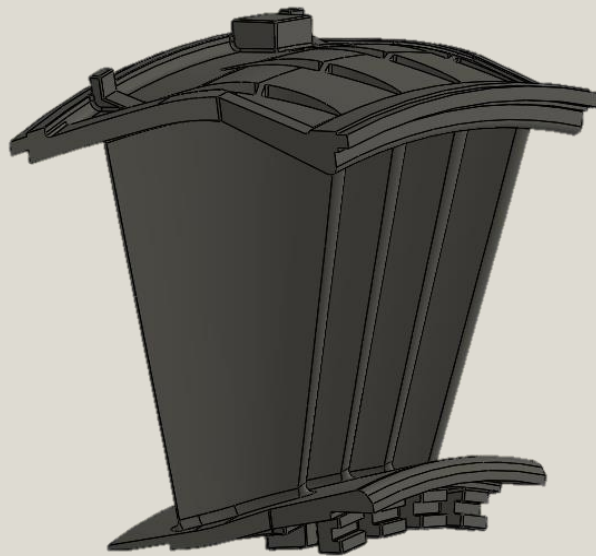


Stage 3 Nozzle Block Redesign



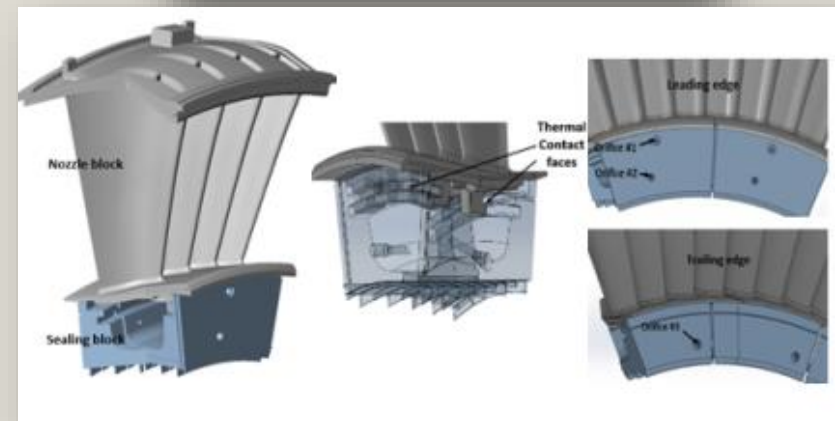
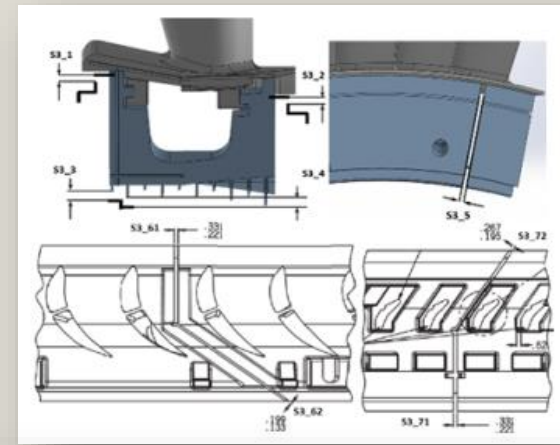
The new SoftInWay stage 3 nozzle block was developed based on the redesigned airfoils, accounting for:

- New airfoil geometry
- Modified internal channels for cooling flow
- New airfoils positioning on nozzle block platforms
- Modified Hub and Shroud



3D CAD model of the New Nozzle Block

Nozzle Block model details

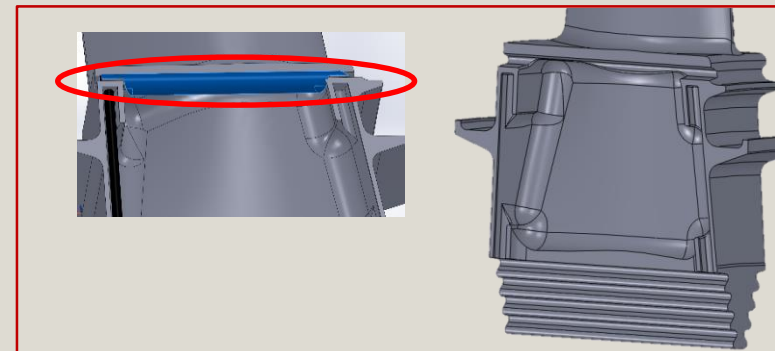
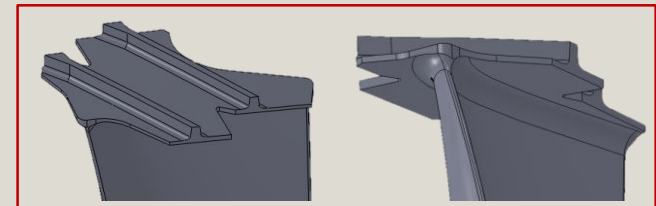
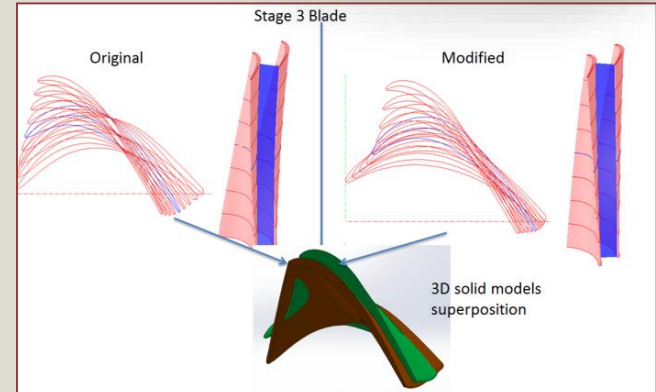


Stage 3 Rotor Blade Redesign



The following features were incorporated in the new design of the blades:

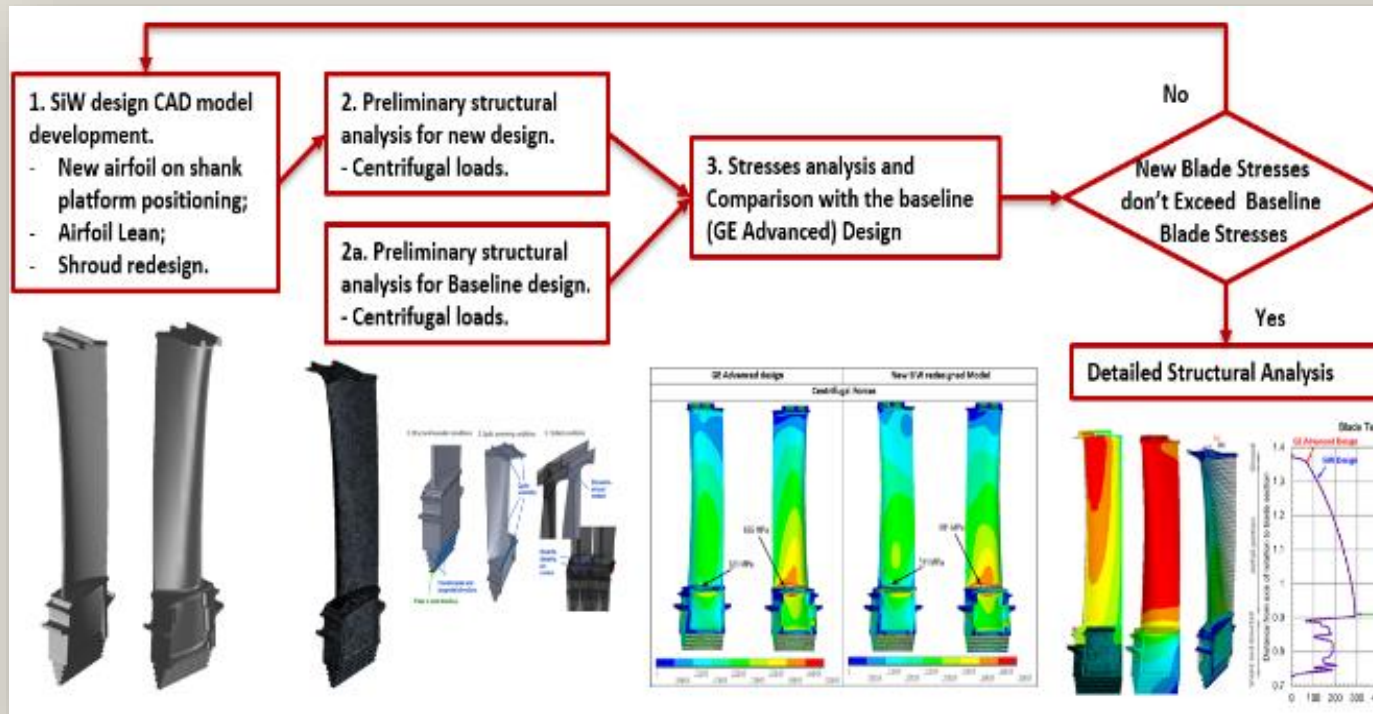
- Airfoil upgrade according to the new 3D aero design.
- Modified shroud design (optimized shape to fit the new airfoil, increased tip shroud fillet to improve resistance to mean and vibration stresses).
- Modified damper surface to minimize stress concentration and damper loading.
- New airfoils position on root block platforms.



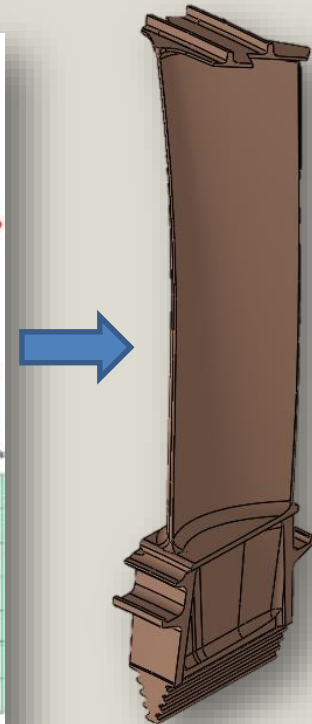
Stage 3 Rotor Blade Redesign



An iterative approach, including design and preliminary structural analysis tasks, has been used to optimize the position of the airfoil/shroud on the original shank/dovetail and balance the stresses due to centrifugal loads.



Rotor Blade Design Process



Rotor Blade 3D CAD model

Coupled Aero-Thermal CFD Analysis

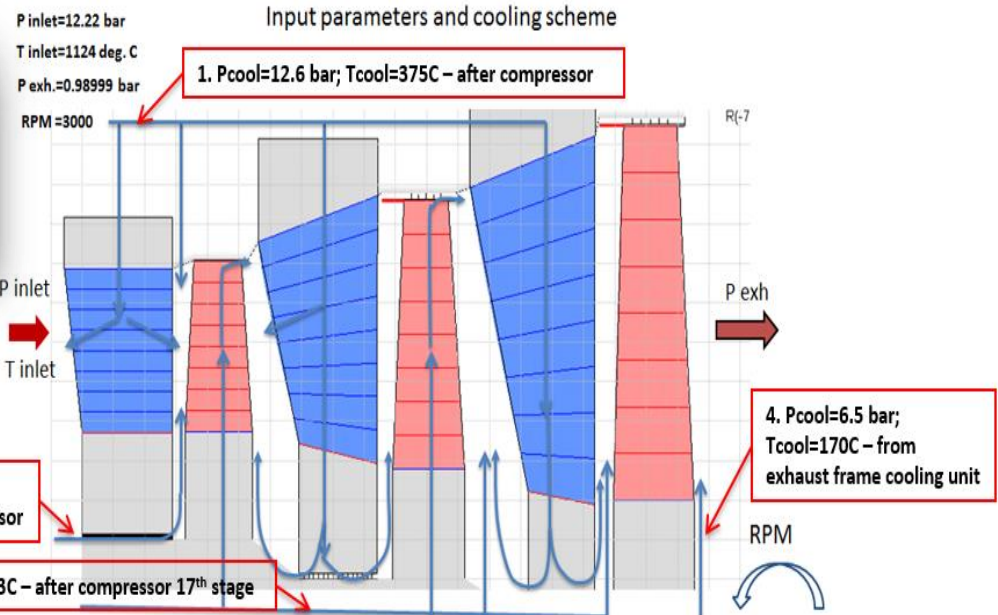


SoftInWay run coupled Aero-Thermal CFD simulations in order to obtain the boundary conditions (pressure distribution and vane/blade body temperatures) needed to perform the detailed structural analysis.

Turbine cooling scheme, temperatures and pressures

Cooling Air Mass Flow Rates per One Row

	kg/s	Stage 1		Stage 2		Stage 3	
		SI	SI	SI	SI	SI	SI
Tip cooling	kg/s	0.00	0.00	0.00	0.00	0.00	0.00
LE cooling	kg/s	4.05	0.00	2.00	0.00	0.00	0.00
TE cooling	kg/s	0.00	0.00	0.00	0.00	0.00	0.00
Hub Endwall cooling	kg/s	0.00	0.00	0.00	0.00	0.00	0.00
Shroud Endwall cooling	kg/s	0.00	0.00	0.00	0.00	0.00	0.00



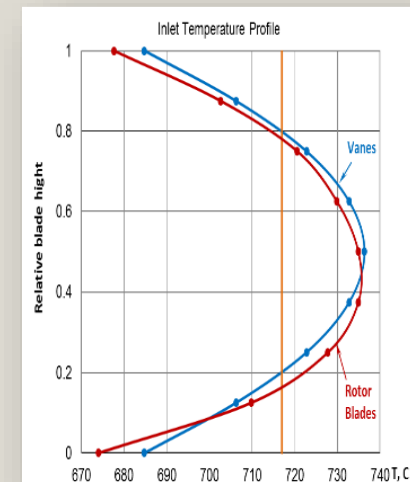
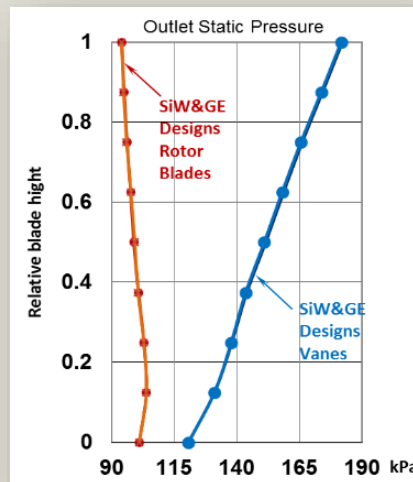
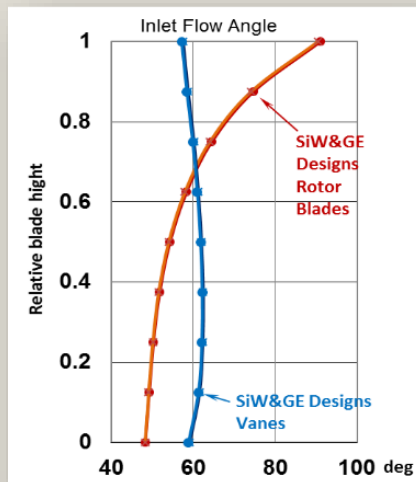
Coupled Aero-Thermal CFD Analysis



SoftInWay calculated the following working gas parameters using AxSTREAM:

- mass flow rate
- inlet pressure radial distribution
- outlet pressure radial distribution
- inlet flow angles
- inlet temperature

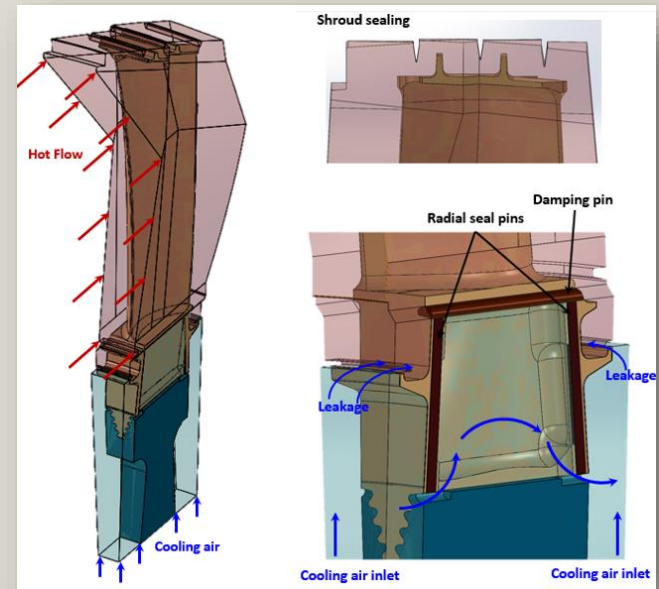
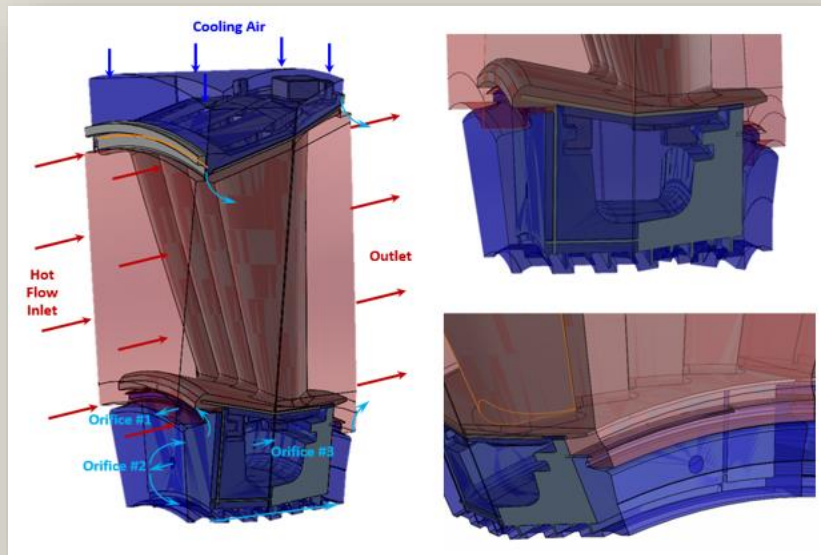
The inlet temperature profiles of the working gas were evaluated and accepted based on SoftInWay's Gas Turbine Experience.



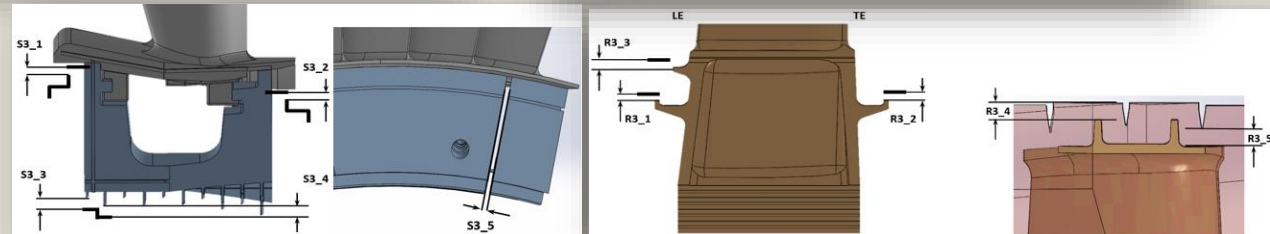
3D CAD Modelling for CFD & Hot Clearances



Detailed Nozzle and Rotor Blade Block CAD model, showing working gas and cooling flows modelling for CFD (including hot flow, cold flow, nozzle and sealing block):



Hot clearances were estimated using a simplified approach based on cold clearances.



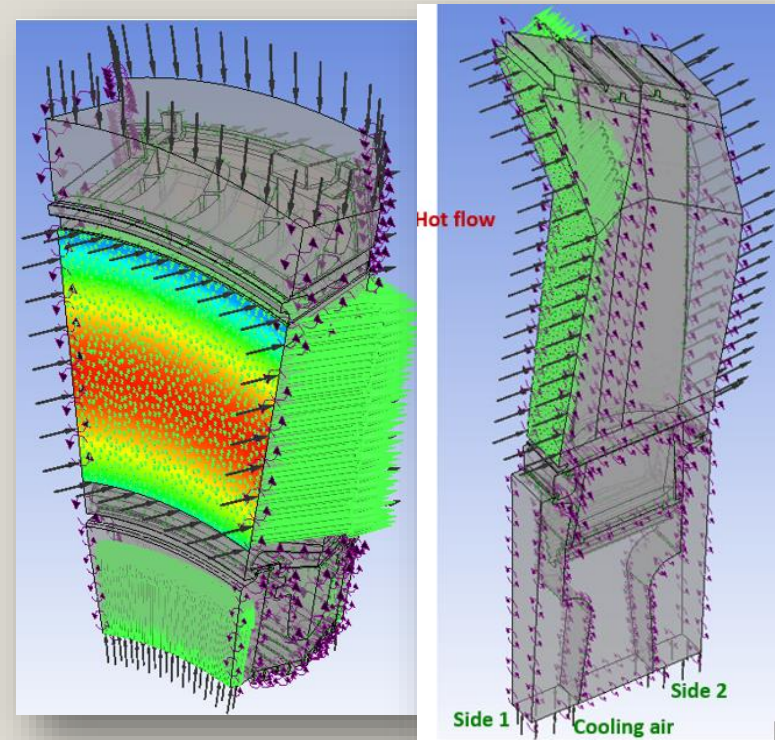
CFD Model



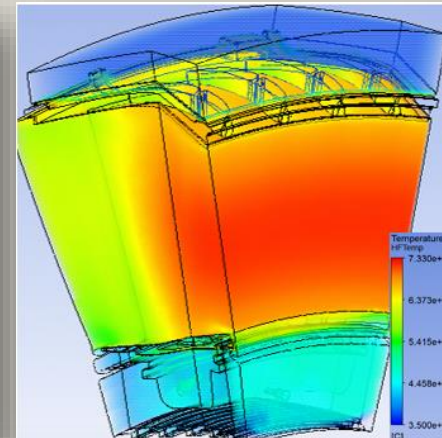
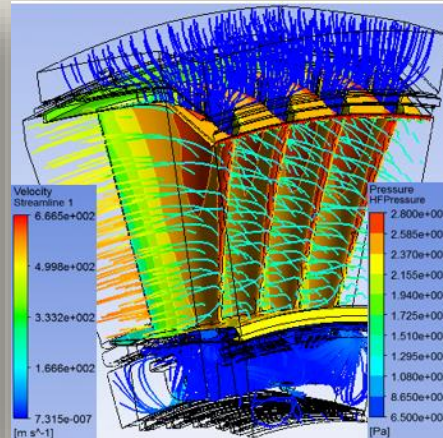
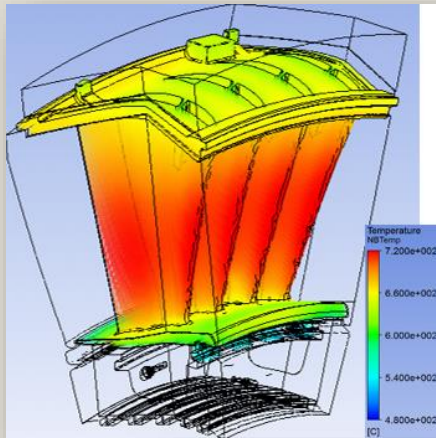
CFD Mesh Creation for Nozzle Block and Rotor Blade



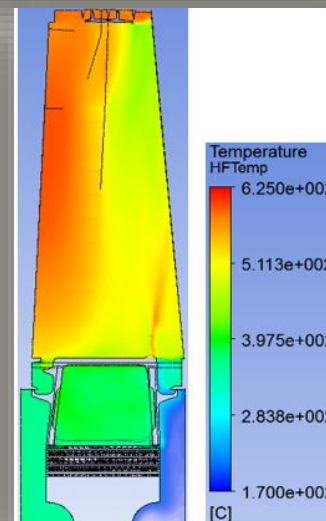
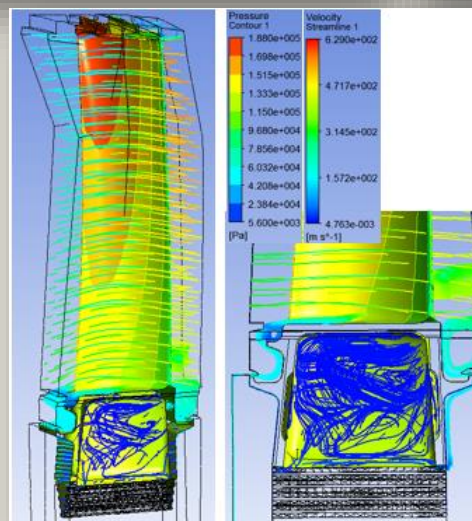
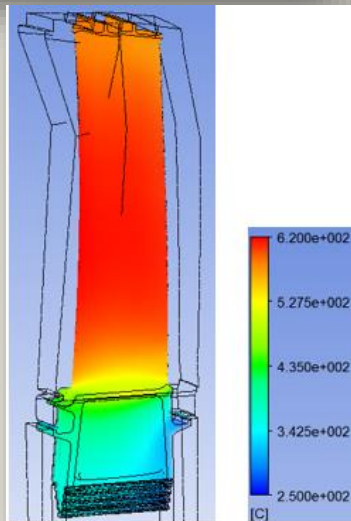
CFD Model Creation for Vanes Block and Rotor Blade



CFD Analysis Results



CFD Analysis Results for the Vane Blocks

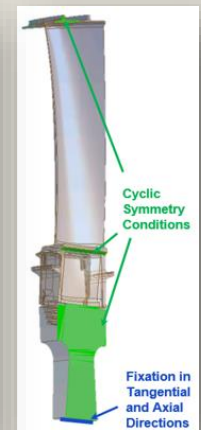
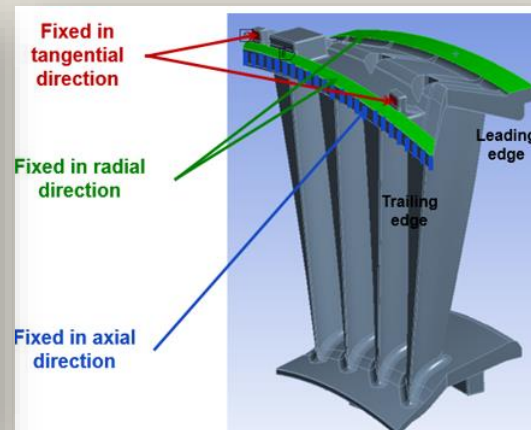
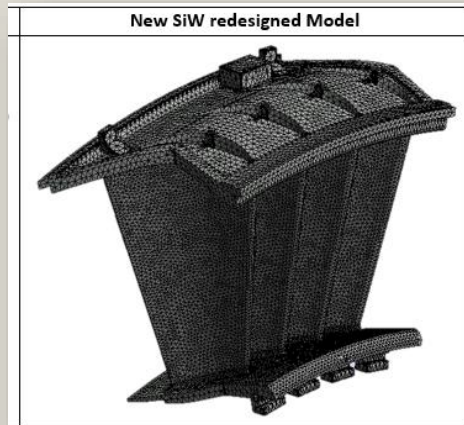


CFD Analysis Results for the Rotor Blade

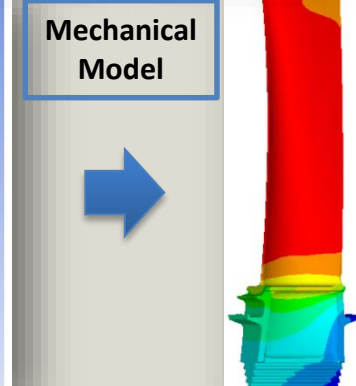
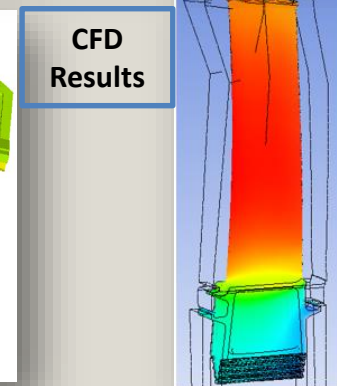
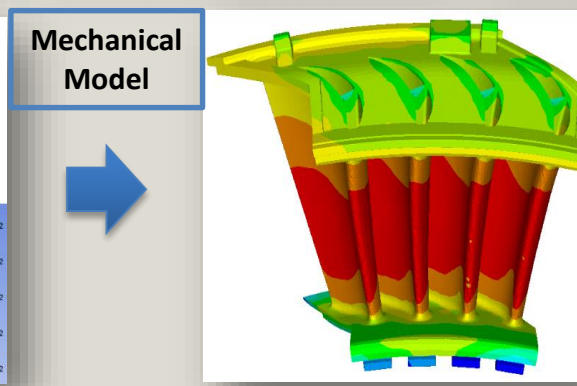
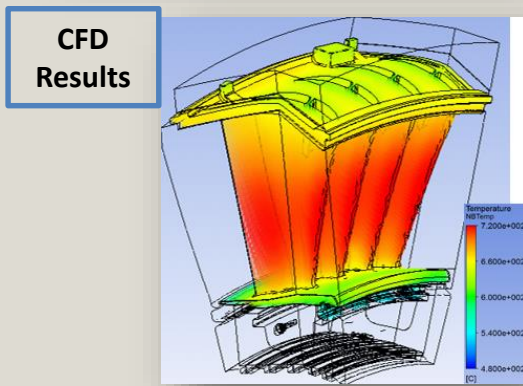
Mechanical and Reliability Analyses



FEA Analysis confirming that structural integrity and lifetime of the new design variant is meeting Structural requirements. Mesh and model are shown below:



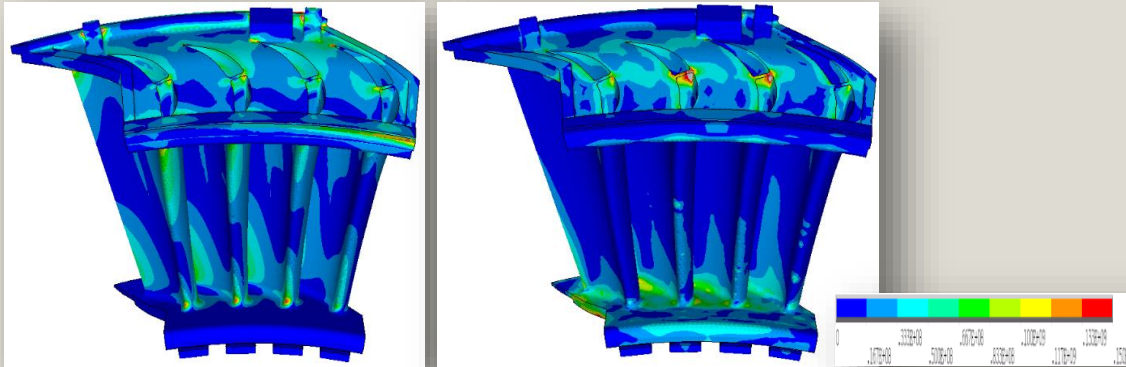
BC CFD export to apply onto Mechanical Model



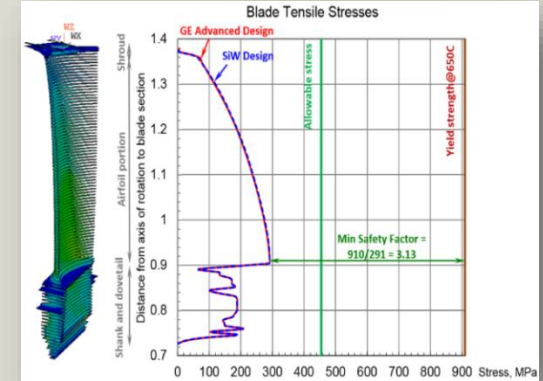
Static Stresses Analysis Results



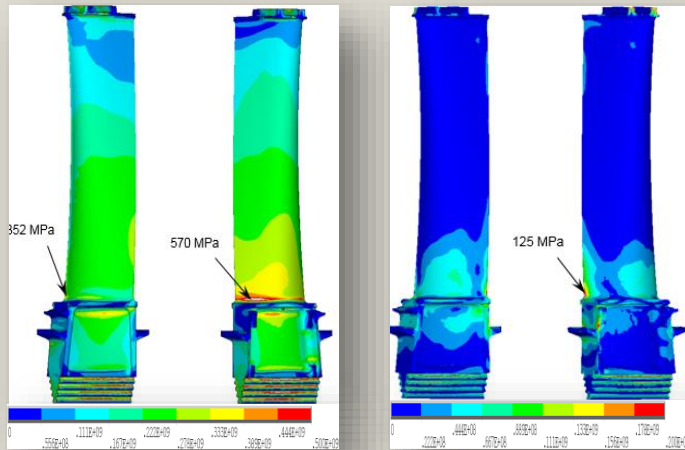
Vane Block Gas/Cooling Air Pressure Stresses (L) and Thermal Stresses (R)



Rotor Blades Average Stresses



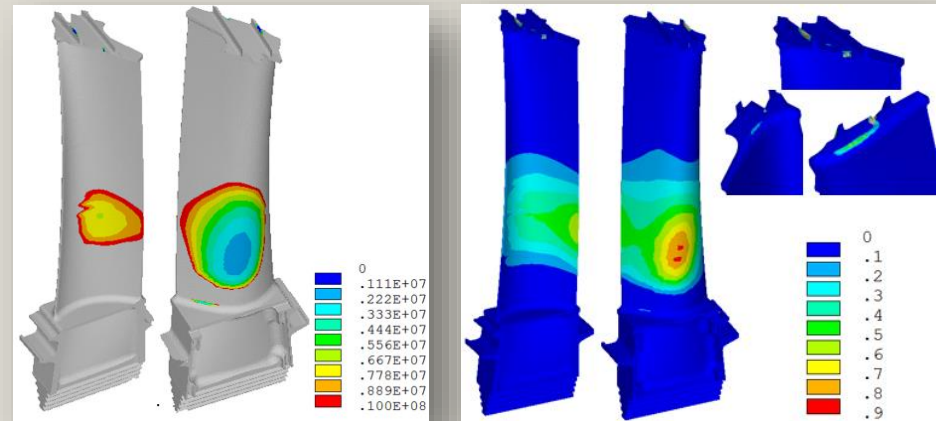
Rotor Blades Stresses Distribution



Combined loading

Thermal stresses

Creep Lifetime and Creep Damage Parameter



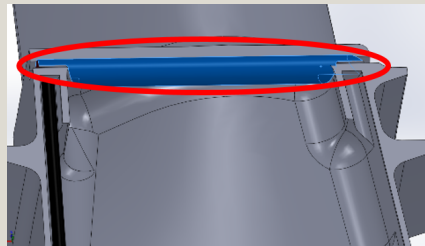
Modal and Interference Diagram Analysis



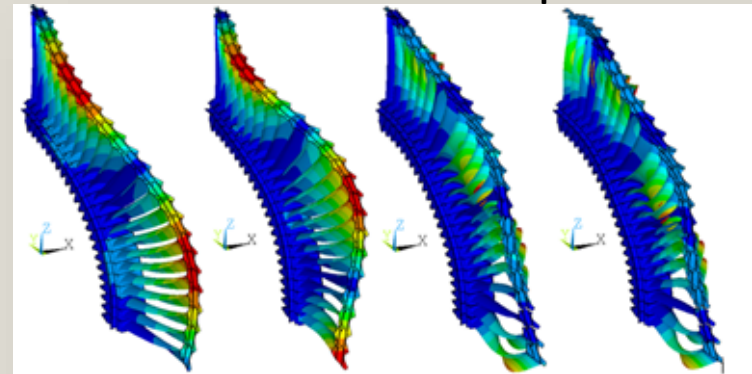
Blading needs to operate safely in resonance condition, for this reason we evaluated interference diagrams and modified the design accordingly to reliability and safety requirements.

Spring elements were used to simulate the dampening effect.

*This method is effectively used during modal analysis in tuning the frequencies to match test frequencies.

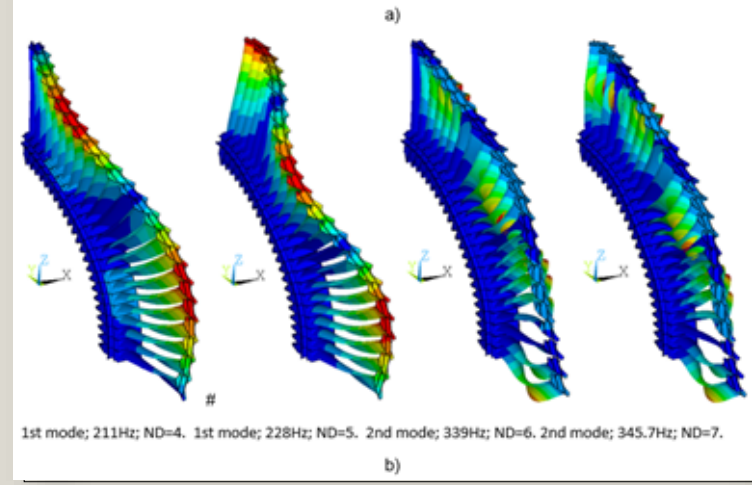
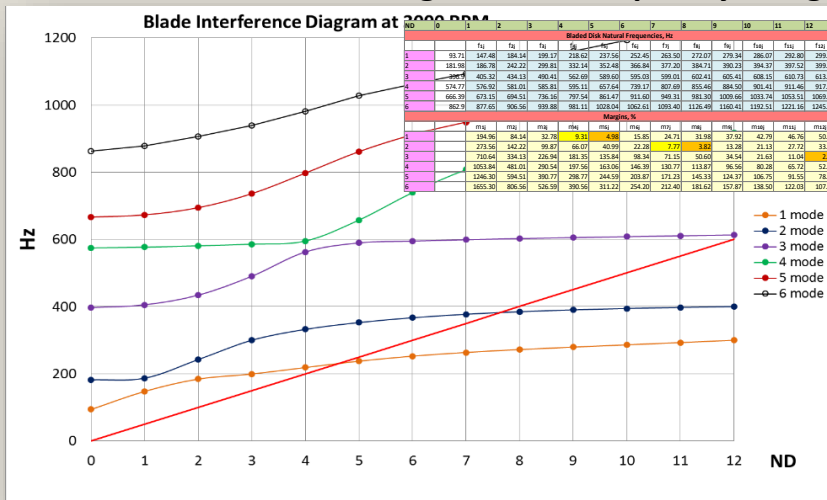


Bladed Disk Modal Shapes



1st mode; 219Hz; ND=4. 1st mode; 238Hz; ND=5. 2nd mode; 377Hz; ND=6. 2nd mode; 385 Hz; ND=7.

Rotor Blade Interference Diagram and Frequency Margins



1st mode; 211Hz; ND=4. 1st mode; 228Hz; ND=5. 2nd mode; 339Hz; ND=6. 2nd mode; 345.7Hz; ND=7.

Conclusions:



- When SoftInWay completed the upgrade project of the GE Frame 9E 126 MW Gas Turbine, our upgraded variant of stage 3 vanes and blades has delivered a ~1% reduction of heat rate for ISO day conditions, in comparison with GE Original design.
- The SoftInWay's aerodynamically optimized stage 3 variant showed performance in line with GE Advanced Design.
- The new stage 3 blades and nozzle block designs developed by SoftInWay have proven high reliability and lifetime.