Process integration between CAD and CAE applications for Isight-based DOE analysis

Ing. Davide Pinna
Ansaldo Sviluppo Energia
Via Lorenzi 8
16152, Genova. ITALY
+39 010 6553249
davide.pinna@aen.ansaldo.it

Ing. Luca Fattore
Exemplar
Corso Vittorio Emanuele II 161
10139, Torino. ITALY
+39 011 435051
luca.fattore@exemplar.com

Abstract: *Product development engineers often use simulation to evaluate the performance of a single design - a part or a system - characterized by a specific CAD representation, specific input data, and materials properties.*

Simple parametric analyses and "what-if?" studies are frequently performed in order to try to improve the design. However, the use of automated optimization and Design-Of-Experiments techniques that allow efficient scientific exploration of the whole Design Space to establish the correlation between the various parameters and to identify optimal solutions is instead less frequent, especially when complex CAD models and various CAE tools are involved.

This paper is focused on CAD and CAE workflow integration for the design of a Gas Turbine vane. The model of the complete process, implemented in the SEE-Fiper environment and involving all the calculation tools, is described.

The goal of the project is to explore the Design Space using a DOE analysis to identify an optimized vane design with geometry that leads to simpler machining and that satisfies both minimum creep life and minimum fatigue life criteria.

Keywords*: CAD, CAE, Collaborative Engineering, Gas Turbine Blade, Gas Turbine Vane, Isight, Multidisciplinary Process, Data and Process Management, Process Automation, Turbomachinery.*

1. Introduction

Ansaldo Energia (AEN) is Italy's leading producer of thermoelectric power plants including process, mechanical, civil, installation and start-up engineering. The production centre is split into three product lines: gas turbines, steam turbines and generators.

Among the components designed in AEN, one of those with higher-tech is certainly the gas turbine vane. It includes various types of challenges: strength, durability, flexibility and maintainability.

The project described in this paper concerns the design and implementation of an automatic multidisciplinary process for the thermo-mechanical analysis of a cooled gas turbine vane, capable of handling both standalone activities and optimization activities. The process starts from a parametric cold CAD model of the internal channel integrated with the CAE model so that changes in the CAD model are automatically reflected in the CAE reference model as multiple analysis runs are launched during the optimization process.

This process has been applied to the exploration of the Design Space for the identification of a new configuration optimized in order to obtain a vane with greater creep and fatigue life and with a lower cooling air consumption and, not less important, to increase the know-how of the experts in 3D modeling and thermo-structural analysis on the use of analytical techniques with parametric CAD models.

As shown in Figure 1, the internal geometry of the vane airfoil examined in this paper is composed of a single channel along its length.

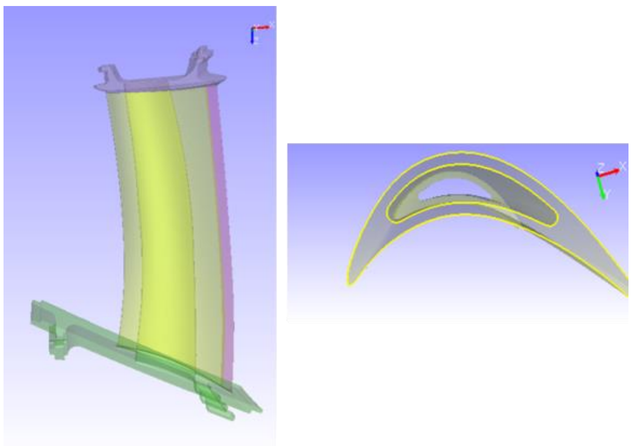

Figure 1. Vane views with internal channel

The disciplines involved in the analysis are 3D modelling, heat transfer, mechanical integrity and lifing (low cycle, creep and high cycle) evaluation. With this automated procedure, all of the tasks concerning the 2D thermal calculation, the 3D thermal calculation, the 3D thermo-structural calculation and the post processing of the results can be launched in a single run, and studies can be performed by varying in a simple way selected parameters at the beginning of the process.

This project provides for the integration of many processes in Isight which can be distributed to many machines in order to optimize all the IT resources (time/license/timeframe) involved in the company.

The activities carried out during this project are:

- ✓ The creation of an automated and repeatable procedure:
  - o Process for parametric CAD model modification
  - o Process for automatic mesh on CAE model
  - o Process for thermo-mechanical analysis and verification
- ✓ The process validation.
- ✓ Design of Experiments analysis (DOE).
- ✓ Results analysis and identification of the optimized solutions.

2. Process Description

This paper describes a multi-disciplinary process for multi-objective optimization of a gas turbine vane. Figure 2 shows the main workflows of the overall process captured in SIMULIA's Isight process integration and design optimization software. This is a multidisciplinary process, very complicated; we use different software (commercial and homemade) and different methodologies and, thanks to Isight, we have very useful management of all of the results with visibility on the state of the vane run to run.

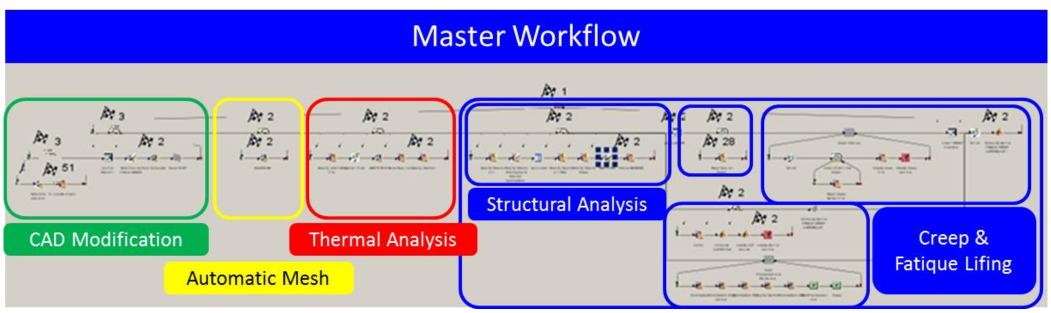

Figure 2. Master workflow

The process is divided into the following workflows:

- ***CAD Modification***
  The CAD modification is based on the UG-NX CAD system and the aim is to update the internal channel section geometry of the vane airfoil in order to obtain a new vane with a complete new internal channel. The internal channel is a body (see Figure 4)

composed of 17 section profiles that describe the shape of the cooling air channel; this body is finally Boolean subtracted from the vane solid body. The 17 channel sections defining the shape of the channel body are parameterized as shown in Figure 3 using 4 geometry dimensions, introduced below:

[mm]RAGGIO_LEADING_EDGE=nn

[mm]RAGGIO_TRAILING_EDGE=nn

[mm]OFFSET_CURVA_PRESSURE_SIDE=nn

[mm]OFFSET_CURVA_SUCTION_SIDE=nn5

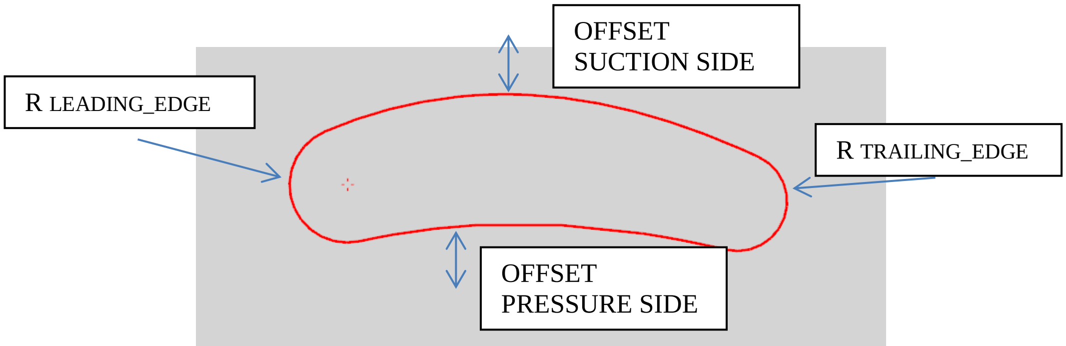

Figure 3. Example of one of the profiles that is updated by the parameters

In Figure 4, one example of the internal channel body operation based on 17 section shapes is shown, in which all of the parametric shapes have been modified independently. In order to avoid sudden curvature changes in the channel shapes in the radial direction, as shown in the right side of Figure 4, *parabolic variation rules* along the vane span have been introduced as **MAIN DOE geometry parameters.**

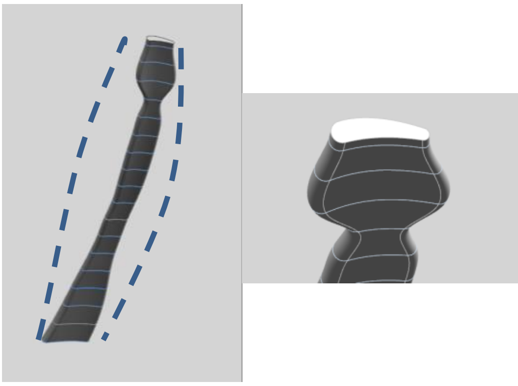

Figure 4. Example of the internal channel body operation based on 17 section shapes when all of the parameters of the shapes have been modified independently; the dashed curves show the parabolic rules used to drive the parameters of all 17 sections in order to avoid an unrealistic channel shape.

The main parabolic channel thickness and radius variation equation along the vane span is based on two geometry characteristics: the maximum position and maximum value of the parabola.

Finally, eight global geometry parameters for the parabolic variation rules along the vane span have been specified as candidates for the DOE analysis to use to define the vane cooling channel shape: max_pos and max_value for trailing and leading radii, and max_pos and max_value of suction side and pressure side thicknesses. Figure 5 shows a number of different geometry variations that can be obtained with these parameters.

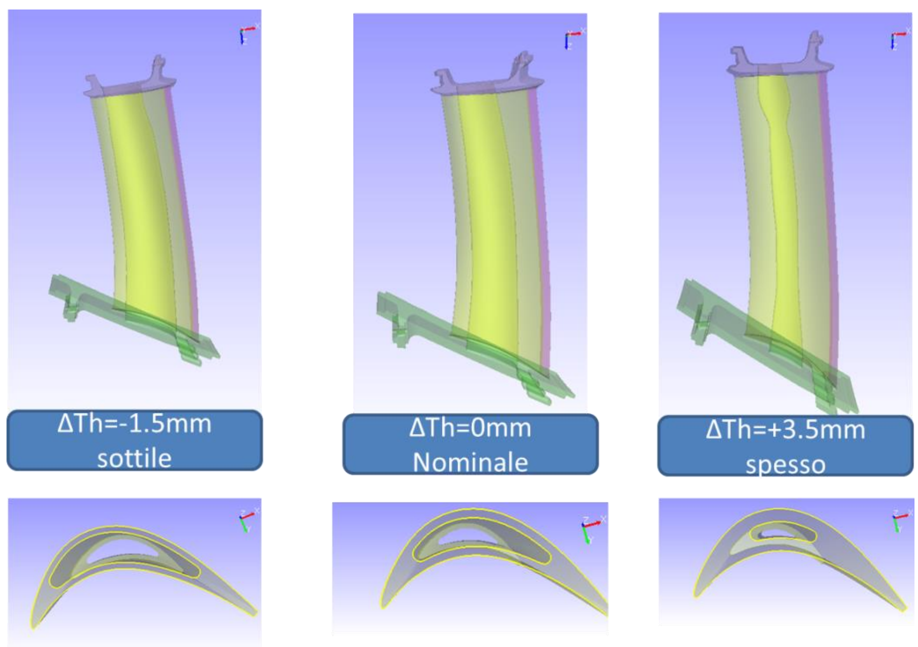

Figure 5. Examples of internal channel geometry variations studied with the DOE process

The Isight process task related to the geometry updates is shown in Figure 6: the first part is a loop on all the channel sections in order to update their geometry parameters based on the parametric parabola shape. Finally the CAD vane assembly is updated with the new section shapes.

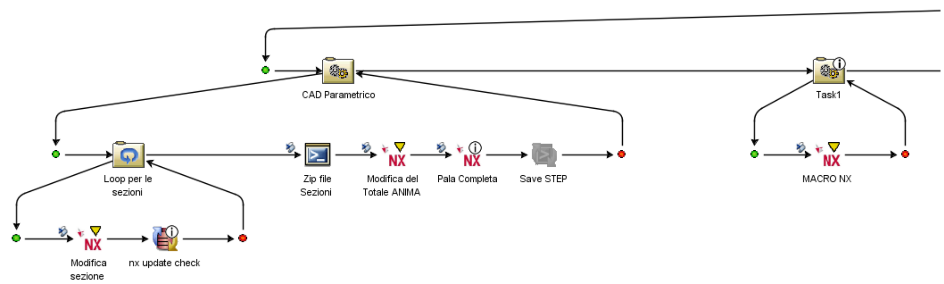

Figure 6. CAD modification process and automatic mesh generation inside UG-NX

- ***Automatic Mesh***

  The second important step in the automation is the **FEM model** creation. This task is performed automatically inside the NX-CAE environment, and the FEM model creation procedure is based on CAD surfaces tagging in order to control the mesh phase and the ANSYS component creation.

  The final result is an ANSYS cdb file with the mesh and the component definition that are used in the next step to apply boundary conditions through some ANSYS macros. The total number of nodes in the automatic process has been limited to 0.5M with respect to the original FEM model used. Figure 7 shows the details of the two FEM models (automatic and manual) compared side by side.

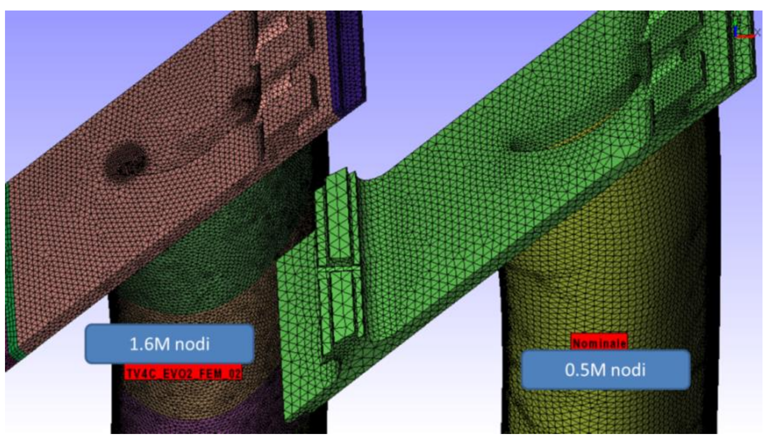

Figure 7. Detail of the original vane FEM model on the left (structural and thermal) and the automatic FEM model on the right created in the Isight process: the number of nodes is 1/3 of the original but the quality satisfies the analysis criteria.

- ***3D Thermal Analysis***

  In this task, a 3D thermal analysis is carried out to obtain the vane's 3D thermal map distribution. The boundary conditions for the 3D thermal analysis are passed directly from a 2D thermal analysis (2D temperature maps, flow network result, 2D HTC distribution). In this implementation, the 2D thermal results are not updated within the new vane channel geometry: instead, a preliminary sensitivity analysis has been performed to check if the introduction of this 2D thermal analysis into the loop is needed, but currently the channel geometry effect on the temperature in the flow has been considered negligible.

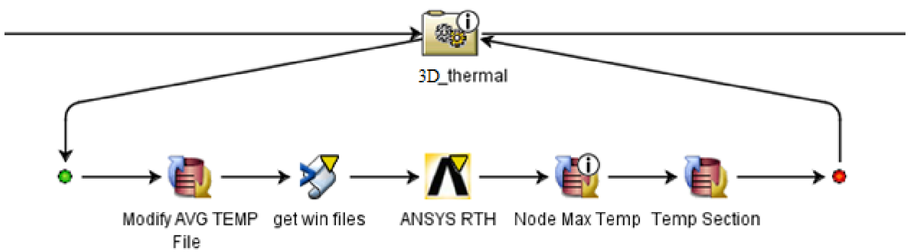

Figure 8. 3D Thermal analysis task

In Figure 9 below, a temperature map comparison between the manual vane analysis versus the automatic one is shown, with the same channel geometry in both cases. The temperature difference is quite small (less than 1°C).

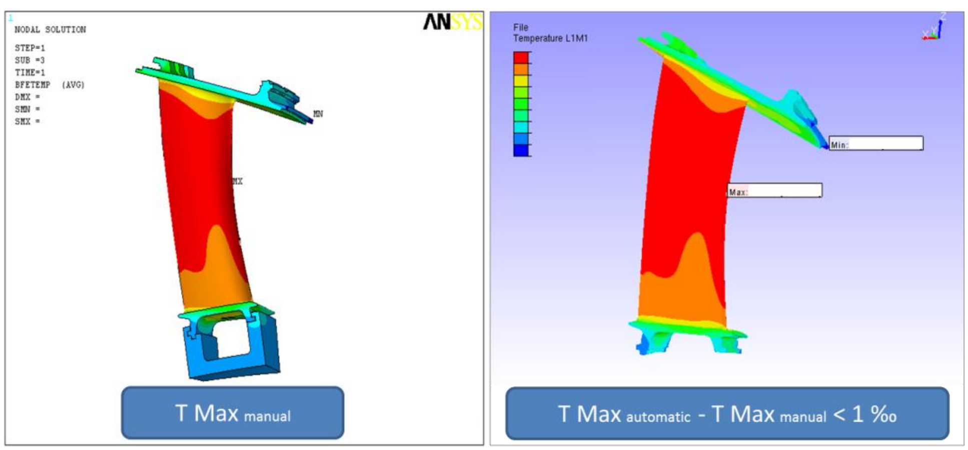

Figure 9. Final temperature map from the thermal analysis: comparison of the manual results (on the left) with the automatic procedure (on the right)

- ***3D Mechanical Analysis***

  In this process, a 3D structural analysis is carried out on the vane, applying structural loads (pressure) and the map of the temperatures obtained with the 3D thermal analysis, to get the final vane's 3D stress map. Figure 10 shows the automated Isight process, and Figure 11 shows the results of the analysis on pressure and suctions sides. Note that a VCOLLAB visualization file is automatically generated from the ANSYS RST results file for easy and efficient evaluation of the results.

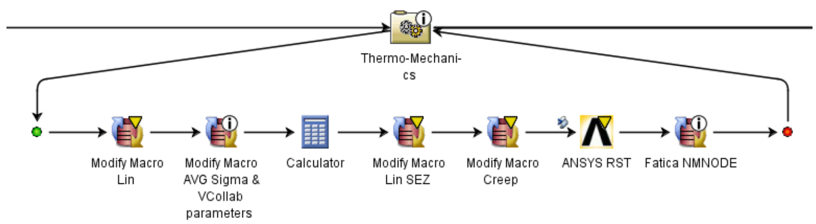

Figure 10. 3D thermal-mechanical analysis process

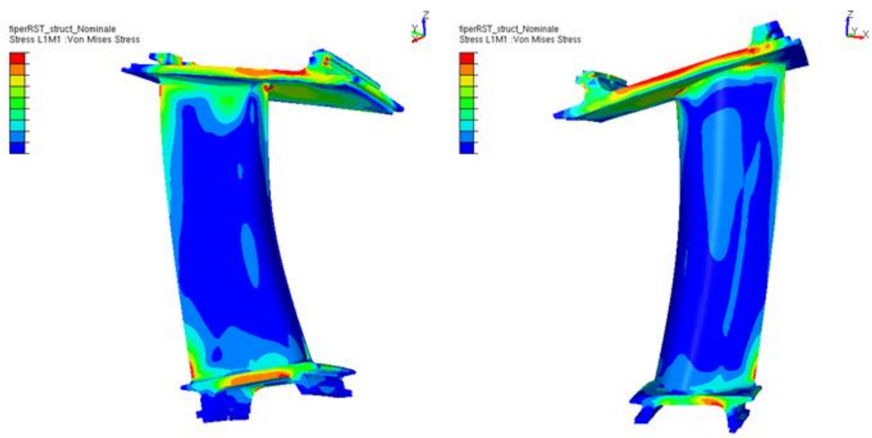

Figure 11. Stresses in the vane, pressure and suction side

- ***Thermo-structural post-processing***

  The post-processing task is divided into three main parts, as shown from Figure 12 to Figure 16. The aim of this task is to evaluate the overall performance of the channel configuration based on maximum Von Mises stress, the creep plastic strain, the LCF (low cycle fatigue) safety factor for the turbine pre-defined working mission, and the final envelope combined (LFC+creep) damage factor.

- Calculation of the margin of safety

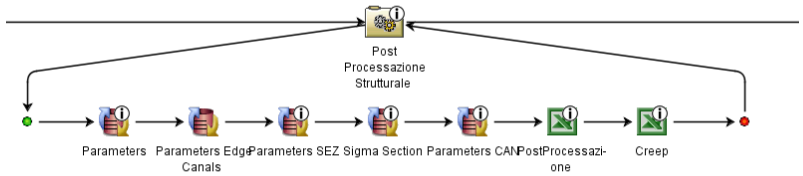

Figure 12. Post processing for margin of safety

The margin of safety is based on Ansaldo's specific requirement. The vane is sliced along 6 planes, then the max stress point is identified at the suction and pressure sides and the stress path is extracted from the max stress point to the shortest distance to the channel. Along the stress path some stress evaluations are performed in order to get the margin of safety comparing the membrane, bending and maximum stress within the material allowable at the specific temperature in the slice. This computation process is automatically performed combining post-processing ANSYS macros and an Excel file (see Figure 13).

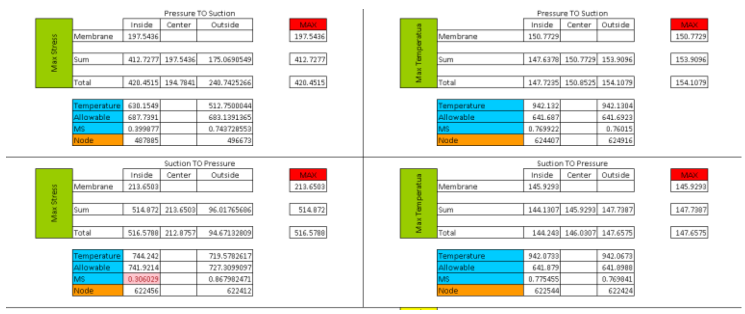

Figure 13. Example of the Excel worksheet used to verify the stress limit in the vane

- Creep analysis (to determine the stress due to creep)

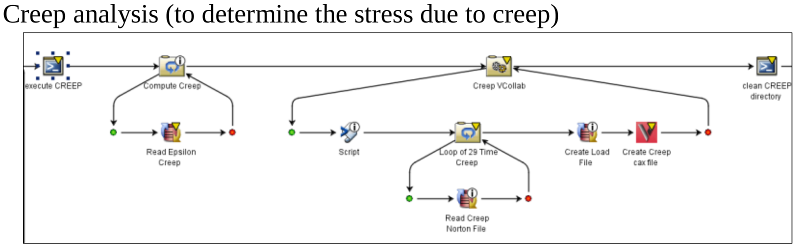

Figure 14. Post processing for creep analysis

In Figure 14, after the ANSYS creep simulation the max creep strain is evaluated in the vane and a VCOLLAB model is created.

- Low cycle fatigue (LCF) analysis (to determine the time of fatigue failure)

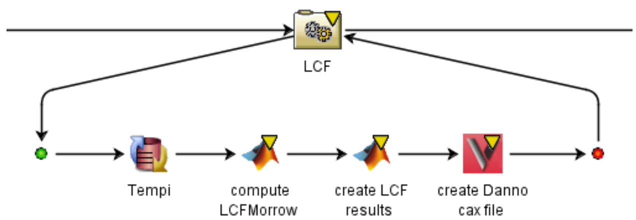

Figure 15. Post processing for LCF analysis

A Matlab in-house code is used to evaluate the LCF fatigue margin of safety combining cyclic stress (computed by ANSYS in the Thermo-mechanical task) simulating a required total amount of startup-shutdown cycles.

- Cumulative damage evaluation

Figure 16. Final integrity margin of safety envelope evaluation

A Matlab in-house code is used to evaluate the cumulative damage, combining LCF fatigue margin of safety with creep damage in order to get the final envelope margin of safety of the vane. This evaluation is performed at different mission scenarios (combining specific hours of startup and number of shutdown-startup cycles).

3. Process Validation

A preliminary validation of the whole process has been performed using the nominal channel design parameters.

In Figure 17, the “official” vane is compared to the one automatically created by the Isight task. The slices created are mainly used by the engineer to see the visual positions of the planes used for the design validation and results extrapolation, but in the automatic Isight process all of the positions are codified in the procedure and no more visual help for the human engineers is needed, so a unique CAD solid is created.

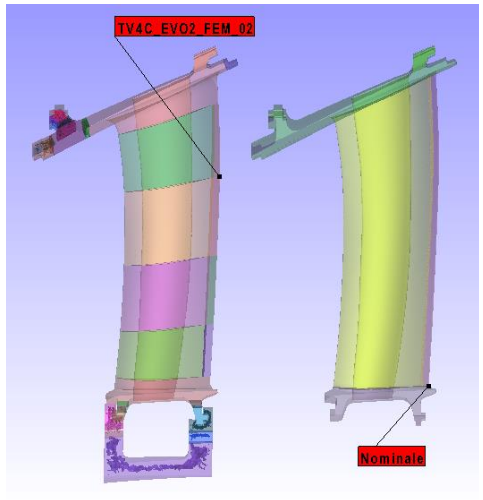

Figure 17. The original CAD model used for the manual vane simulation is sliced (on the left); the automatic procedure creates a unique solid (on the right, the nominal DOE configuration)

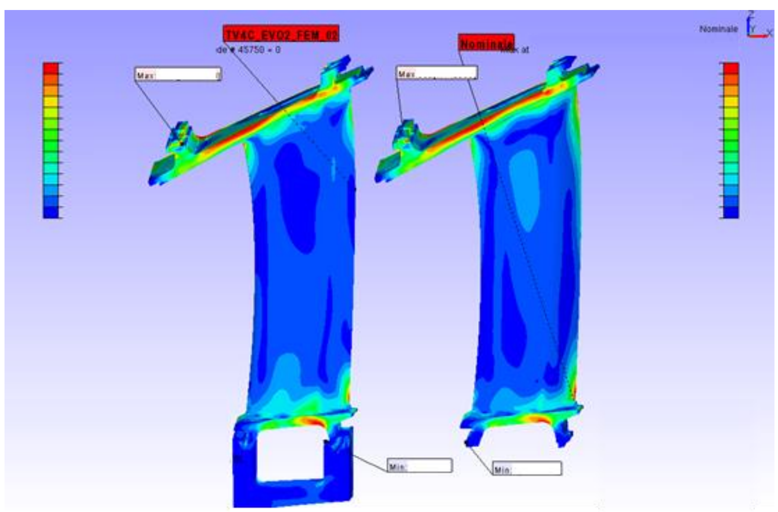

Figure 18. The stress map from the mechanical-thermal analysis: comparison of the manual results (on the left) with the automatic procedure (on the right)

In Figure 18, the Von Mises stress contour from the official manual vane stress analysis is compared to the analysis produced with the automatic Isight process. Some differences are apparent, but the critical location and the global behavior are matched.

4. Results

In Figure 19, a relevant subset of geometry configurations obtained from the DOE study is shown. The max stress, max temperature and max creep strain results for each configuration have been evaluated; the table of results shows how increasing the ***mean*** vane thickness of the airfoil profile leads to a double effect of increasing the creep strain at the training edge (TE) while decreasing the strain at the leading edge (LE). However, the leading edge is more critical, so a solution with a thick airfoil is preferable. In any case, the vane has significant margin before the critical lifing condition is reached.

As shown in Figures 20 and 21, the stresses and the temperatures are not affected by variations in the vane airfoil thickness. Also, the leading and trailing edge radii have only a second order effect on the creep of the vane.

				stress blade [Mpa]		temp blade	Strain CREEP blade [%]	
caso, note	thickness OFFSET [mm]	trailing radius %	leading radius %	TE	LE	max	TE	LE
sottile	-1,5	100	100	N+2	N-9	N	N -0,013	N+0,008
nominale_DOE	0	100	100	N	N	N	N	N
	2,5	100	100	N+2	N+4	N+0,7	N+0,0096	N-0,004
	3	100	100	N+3	N+4	N+0,9	N+0,011	N+0,004
spesso	3,5	100	100	N+3	N+3	N+1	N+0,011	N+0,001
spesso rag racc +	3,5	110	110				N+0,010	N+0,0032
spesso rag racc +	3,5	110	120				N+0,0097	N-0,0043

Figure 19. Some relevant configurations and the overall results obtained from the DOE campaign: N is the Nominal value

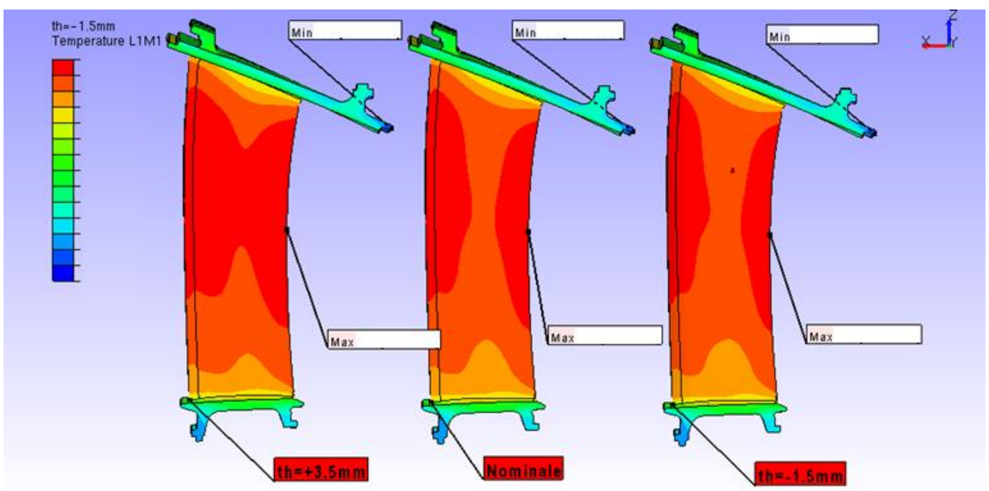

Figure 20. The temperature distribution with 3 different relevant thickness configurations

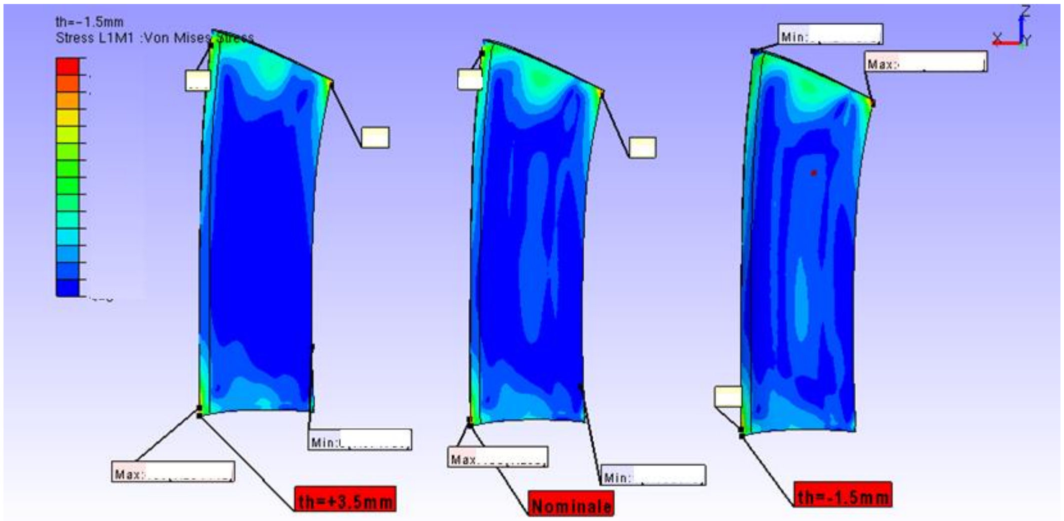

Figure 21. The stress distribution along the vane for 3 different airfoil mean thicknesses

5. Conclusion

The DOE results on the turbine vane object studied in this paper help to illustrate some interesting considerations regarding the internal channel design.

- No critical lifing condition is violated as a result of the channel thickness and radius distribution along the vane span; therefore an increase in the thickness may lead to an overall lower creep strain and it will not significantly affect the life of the part.
- Innovative considerations in the internal channel design coming from *manufacturing* and/or *quality* approach can be evaluated without compromising the structural requirements of the vane.

This Isight project has shown the potential benefit of an automatic procedure that involves a parametric CAD model in all the steps of checking the design requirements for the final design validation. Some lessons learned can be summarized:

- Creating an automatic and repeatable procedure for design studies provides the ability to track all the information/files/methods from the CAD definition to the FEM validation so that they can be re-used in future studies.
- The increase in knowledge of the multidisciplinary CAE tools achieved by the engineer involved in the development of the Isight process has enabled a new approach, leading to a more powerful and thorough automatic design exploration procedure compared to the classic trial-and-error manual experience.

- By enabling the quick exploration of new and innovative designs, the engineer's knowledge in the specific field of interest is increased, thus encouraging him to explore beyond heritage configurations and drive forward with new innovative approaches and designs.

6. Bibliography

The following papers have provided inspiration for this project and have been the starting point for the development of our innovative contribution to the design of the gas turbine.

1. Cofer J.I., and Hahn Y., "Design Study of Dovetail Geometries of Turbine Blades using Abaqus and Isight," ASME paper GT2012-68566, ASME Turbo Expo, Copenhagen, Denmark, 11-15 June 2012.
2. Di Sisto P., Parodi M., "New Simulation Process for the Life Management of the Gas Turbine Rotors," ASME paper GT2013-96033, ASME Turbo Expo, San Antonio, Texas, 03-07 June 2013.
3. Karl A., "Simulation Driven Design Enabling Robust Design," presented at the 2010 SIMULIA Community Conference, 25-27 May 2010.
4. Mattone M., Maggiore M., and Di Sciuva M., "Integrated Environment for Virtual Product Development," Greek-Italian Aeronautics Days: Growing by Sharing, Turin, Italy, 27 October 2006.
5. Panchenko Y., Moustapha H., Mah S., Patel K., Dowhan M.J., and Hall D., "Preliminary Multi-Disciplinary Optimization in Turbomachinery Design," presented at the NATO RTO AVS Symposium, Paris, France, 22-25 April 2002, and published in RTO-MP-089.
6. Pinna D., and Cittadella F., "DOE Analysis for Internal Cooling Configuration of Gas Turbine Blade," presented at the 2013 SIMULIA Community Conference, Wien, Austria, 22-24 May 2013.
7. Pinna, D., and Macciò, M., "Collaborative Engineering Process for Multidisciplinary Optimization of a Gas Turbine Component," presented at the 2011 SIMULIA Community Conference, Barcelona, Spain, 17-19 May 2011.
8. Pinna, D., "L'ingegneria Collaborativa: l'esperienza in Ansaldo Energia," Master in "Innovazione tecnologica e sviluppo prodotti per la generazione di energia," Università degli Studi di Genova, Ansaldo Energia, 2010.

7. Acknowledgments

The authors wish to thank Dr. Alberto Federici and Dr. Francesco Cittadella for his contributions during the process implementation.