DOE Analysis for Internal Cooling Configuration of Gas Turbine Blade

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Abstract

Today manufacturing companies are more and more often characterized by a growing complexity of products and processes. Projects need the participation of teams that have to collaborate in a multidisciplinary and integrated way.

The gas turbine blade design process is typically multidisciplinary where the variables of one discipline can strongly influence the results of other disciplines.

For this reason it is important to have a single simulation process that can correlate the different I/O and allow an investigation of the entire Design Space, in order to verify even those solutions that are hardly predictable.

The application of optimization techniques and simulation-driven design improve and accelerate the multidisciplinary simulation analysis, in order to obtain the best product in terms of technological innovation, performance and quality, starting with the early design conception.

This paper is focused on a gas turbine blade where both the thermal and mechanical disciplines are involved. The model of the complete process, implemented in the SEE-Fiper environment and involving all the calculation tools, is described. The target of the project is the Design Space exploration (DOE Analysis) to identify a better internal cooling configuration in order to achieve a blade with simpler machining that also satisfies the criteria of minimum creep life and minimum fatigue life. The results obtained by considering many optimization variables are reported.

1. Introduction

Ansaldo Energia (AEN), a company of the Finmeccanica Group (55%) and First Reserve (45%), 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 blade. 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 thermo-mechanical analysis of gas turbine blades, capable of handling both standalone activities and optimization activities, and that requires the launch of multiple runs of the same process.

This process has been applied to the exploration of the Design Space for the identification of a new configuration of internal cooling, in order to obtain a blade with greater creep and fatigue life and with a lower air consumption.

As shown in Figure 1, the internal geometry of the airfoil of the blade examined is composed of 13 channels along its length that supply cooling air in order to reduce the metal temperature. Special provisions (ribs) are applied on the surface of these channels in order to increase the heat transfer.

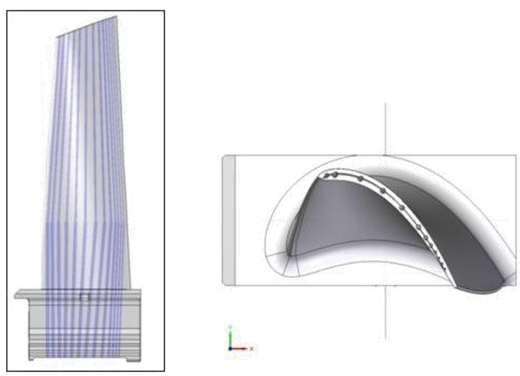


Figure 1. Blade views with internal cooling channels (left) and cooling flow exit holes at blade tip (right)

The disciplines involved in the analysis are the heat transfer and mechanical integrity.

The activities carried out are:

- ✓ The creation of an automated and repeatable procedure for the thermo-mechanical calculation.

- ✓ The implementation of macros for the calculation and the post-processing of the FEM results.
- ✓ The process validation.
- ✓ Design of Experiments analysis (DOE).
- ✓ Results analysis and identification of the optimized solutions.
- ✓ An approach to the distributed calculation.

2. Process Description

This paper concerns a multi-disciplinary process for multi-objective optimization of a gas turbine blade. 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 manage of the all results and to have visibility on the blade state run to run.

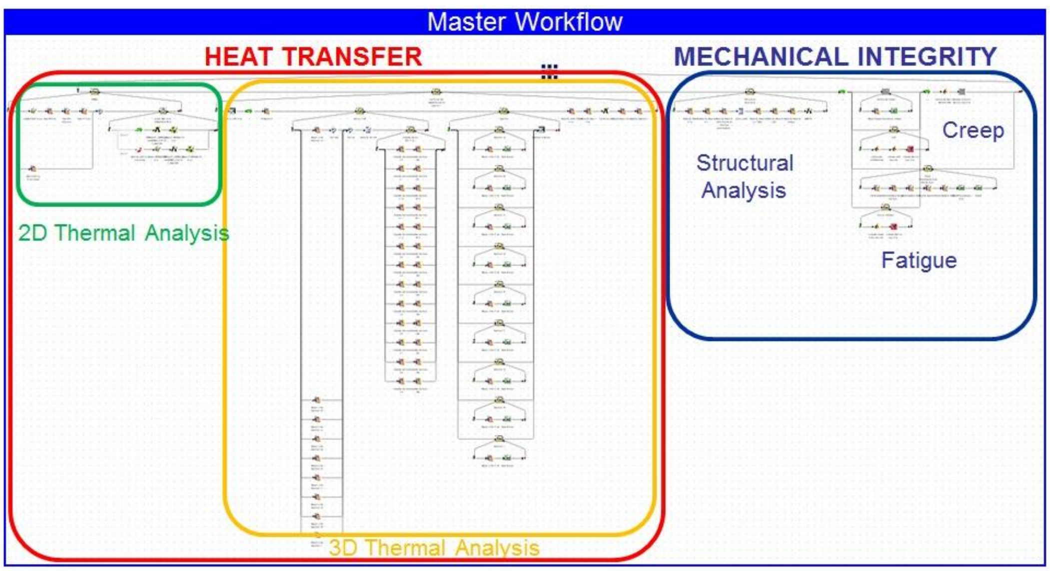


Figure 2. Master workflow

The process is divided into the following workflows:

- ***2D Thermal Analysis***
  In this process, a 2D thermal analysis is carried out to obtain thermal maps of the blade's cross-sections.

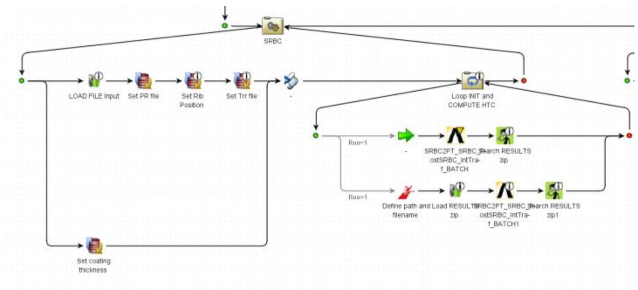


Figure 3. 2D thermal analysis

Figure 3 shows the components of the 2D thermal analysis process, including the input 2D mesh slices, heat transfer coefficient (HTC) values, boundary temperatures, thermal material properties, and output 2D temperature maps, flow network results, and 2D HTC distribution.

- ***3D Thermal Analysis***

  In this process, a 3D thermal analysis is carried out to obtain the blade's 3D thermal map. The boundary conditions for the 3D thermal analysis are passed directly from the 2D thermal analysis (2D temperature maps, Flow network result, 2D HTC distribution).

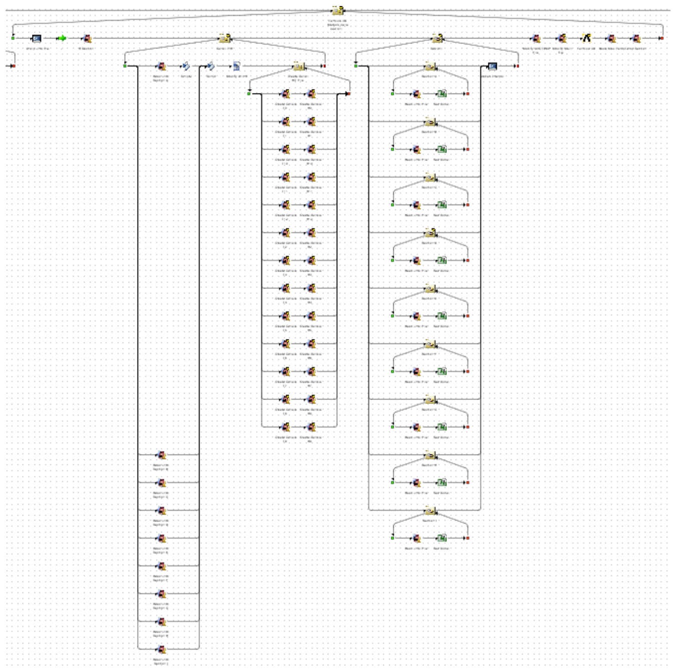


Figure 4. 3D thermal analysis

Figure 4 shows the components of the 3D thermal analysis process, including the input 3D mesh, HTC values for the cooling channels from the 2D analysis, HTC values for the external profile, temperatures applied on the cooling channels from the 2D analysis, temperatures applied on the external profile, fixed HTC values for the platform and fir tree, the cooling flow network and the output 3D temperature maps.

- ***3D Thermo-Structural Analysis***

  In this process, a 3D thermo-structural analysis is carried out on the blade, applying various structural loads (pressure, centrifugal force, etc.) and the map of the temperatures obtained with the 3D thermal analysis, to obtain the blade's 3D stress map.

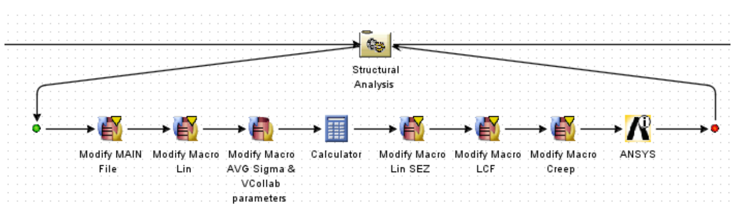


Figure 5. 3D thermo-structural analysis

Figure 5 shows the components of the 3D thermo-structural analysis, including generation of the input 3D mesh, 3D thermal map (Thermal LOAD), structural material properties, pressure load, temperatures applied on the external profile, centrifugal load, constraints and output stress distribution.

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

  The thermo-structural post-processing is divided into three parts, as shown in Figures 6 through 8:

  - Calculation of the margin of safety

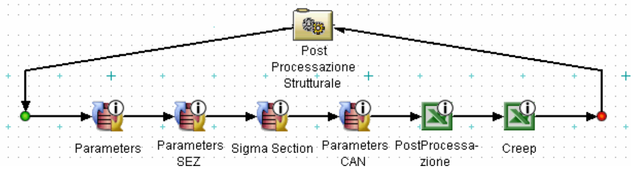


Figure 6. Post processing for margin of safety

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

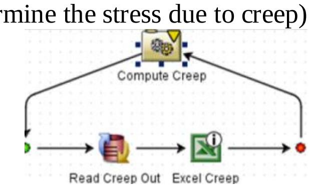


Figure 7. Post processing for creep analysis

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

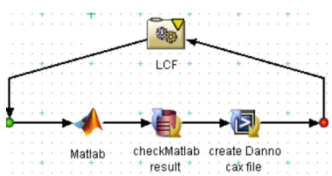


Figure 8. Post processing for LCF analysis

These processes verify that all the criteria for mechanical integrity are respected.

In order to maintain control of the blade for creep analysis with the Larsson-Miller formula and to reduce dispersions of inconclusive results (peak loads and/or temperature due to the proximity of the boundary conditions or mesh), we decided to check 41 points fixed for each section (9 sections in our case), keeping track of them using dedicated Excel worksheets, as shown in Figure 9.

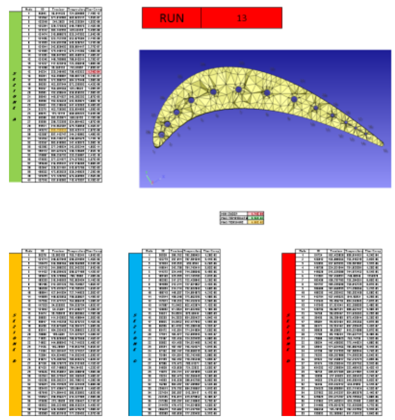


Figure 9. Examples of Excel data sheets

The LCF process allows us to determinate the fatigue life; in this case we use a Matlab tool created in-house by Ansaldo Energia.

With this automated procedure, the individual processes for the 2D thermal calculation, the 3D thermal calculation, the 3D thermo-structural calculation and the post processing of the results can all 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 not only the result (i.e. to find a more efficient cooled blade), but also the use of company computing resources to avoid overloading a single machine.

Using this process, we have carried out a DOE (Design of Experiments) analysis composed of 4 different groups to study the trends of results for various cooling passage rib configurations. To make these analyses, we have identified a number of input parameters that can be changed by Isight in order to see their influence on the output parameters and to use as design parameters for optimization.

3. Process Validation

Analyses with a high number of runs need to rely on workflows with low computation times. To this end, we have used a coarse explorative model with 550,000 nodes, as shown in the left side of Figure 10, to reduce analysis time while maintaining an acceptable accuracy of the results. This is a qualitative approach.

The detailed model of about 2 million nodes shown on the right side of Figure 10 will be used for the certification of the blade itself, with the high number of nodes producing results with higher accuracy. This is a quantitative approach.

It is very important to validate this model and validate the process.

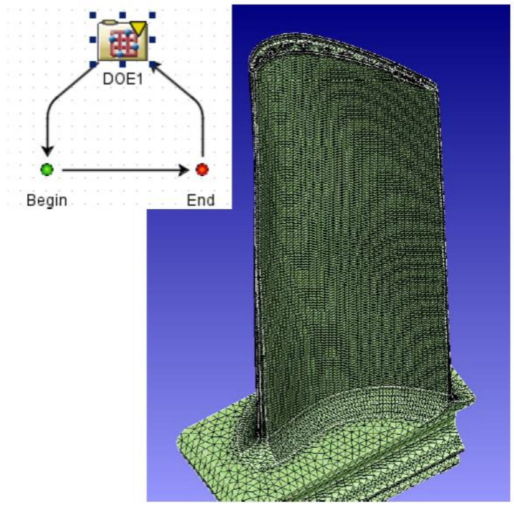
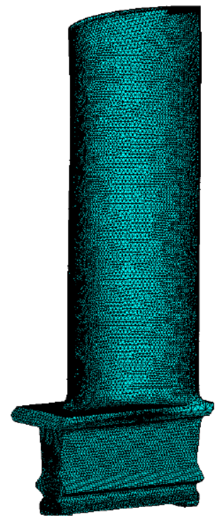
Coarse Model	Detail Model
	

Figure 10. Coarse model and detailed model

As illustrated in Figure 11, with the coarse model it is possible to explore more configurations and to find the optimal solution, while with the refined model you can produce a precise analysis for final certification.

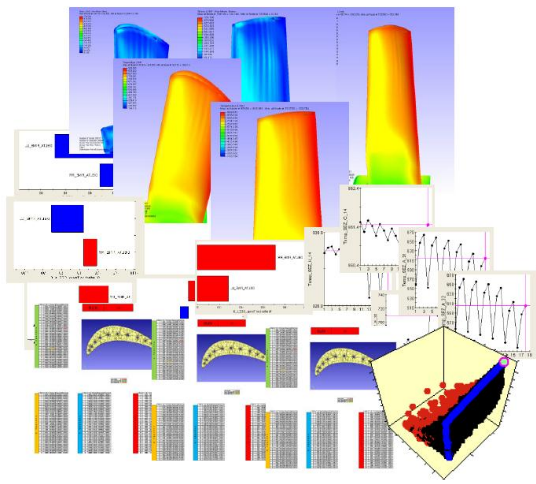
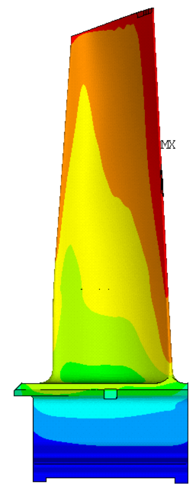
Explorative Approach	Standard Approach
	

Figure 11. Explorative approach and standard approach

We have introduced into the workflows a number of simplifications in order to obtain an "exploratory model" to examine multiple configurations and find the optimal result, and a "standard model" for the final verification of results.

All simplifications made in the methods have been appropriately validated through comparison of results with those certified by standard procedures.

The mechanical loads are the same for all configurations, and in this analysis changes are made only to the thermal load. The parameter of validation is the temperature.

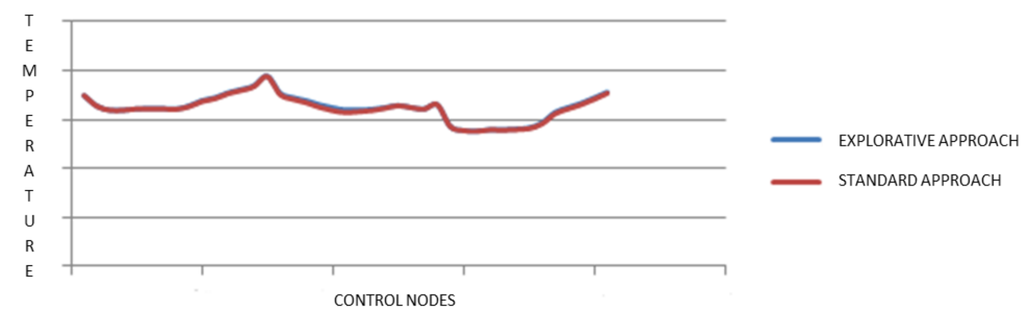


Figure 12. Example of validation

As shown in Figure 12, when we compare the results from the exploratory approach with the standard approach, we obtain a Delta Average Temperature difference of 0.13% and a maximum temperature difference of 1% in the first section. We considered these results acceptable to validate the approximations made in the exploratory approach.

4. DOE Analysis

To study the design space, we identified four parameters of variation and three different DOE analyses that consider the variation of the portion of the channels provided with ribs.

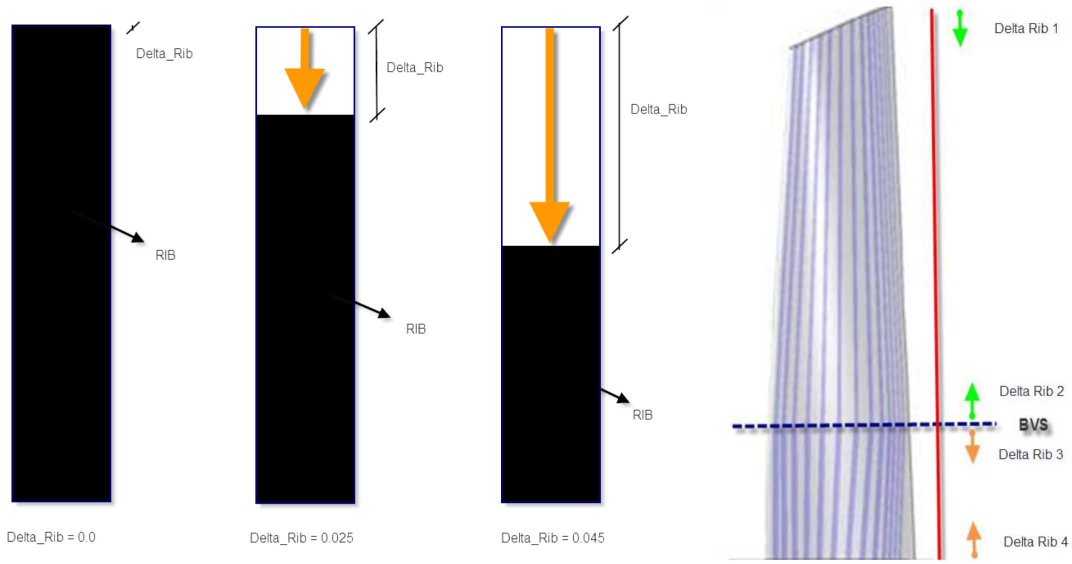


Figure 13. Parameters for DOE analysis

Figure 13 illustrates the parameters used for the DOE analysis, Delta Rib. Delta Rib is a variation of the proportion of ribs in the channel. In the figure, the black rectangle is the portion including ribs while the white rectangle is the smooth channel that does not include ribs. If the Delta Rib value is increasing the smooth channel portion increases. We have four parameters shown in Figure 13: Delta Rib 1, Delta Rib 2, Delta Rib 3 and Delta Rib 4. These channels have different sections - above the BVS line the sections are bigger than the ones below the BVS line. So, we decided to run three different DOE analyses using different combinations of Delta Rib values:

- DOE 1 - variation of the value Delta Rib 1 and Delta Rib 4.
- DOE 2 - variation of the value Delta Rib 1 and Delta Rib 2.
- DOE 3 - variation of the value Delta Rib 3 and Delta Rib 4.

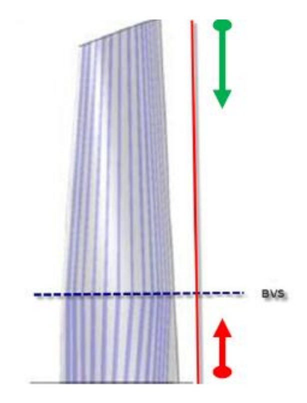
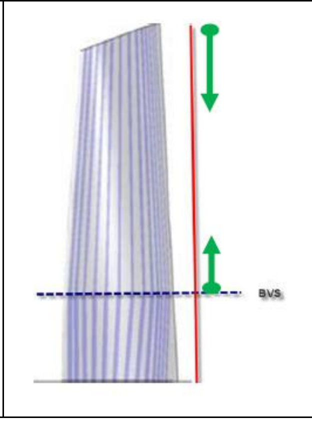
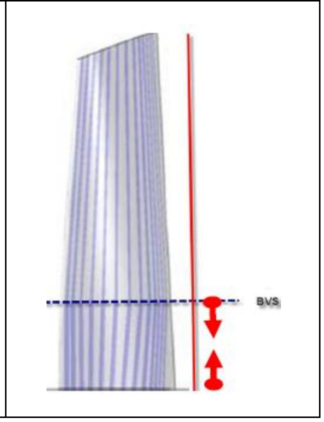
DOE 1	DOE 2	DOE 3
		

Figure 14. Parameter variations

From the first DOE analysis you can note how the elimination of ribs in the cooling passages of the blade leads to a variation of the temperature to be controlled, although it is not excessive. This is because the absence of ribs in the channel leads to a decrease in pressure losses; and since the pressures at input and output of the channel are constant, the pressure difference will cause the cooling flow to increase even more in the first sections of the blade.

The results of the first DOE show that the blade performs well even in the absence of ribs, as the analysis was carried out taking into account the channels as though they were all smooth and the objective was to minimize the flow of cooling air. Without adjusting platelets that regulate the cooling air flow or inserting more ribs, the only way to reduce the cooling flow rate of the blade is to reduce the diameters of the holes in of the blade, as shown in Figure 15.

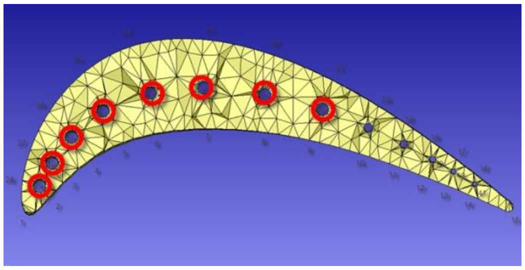
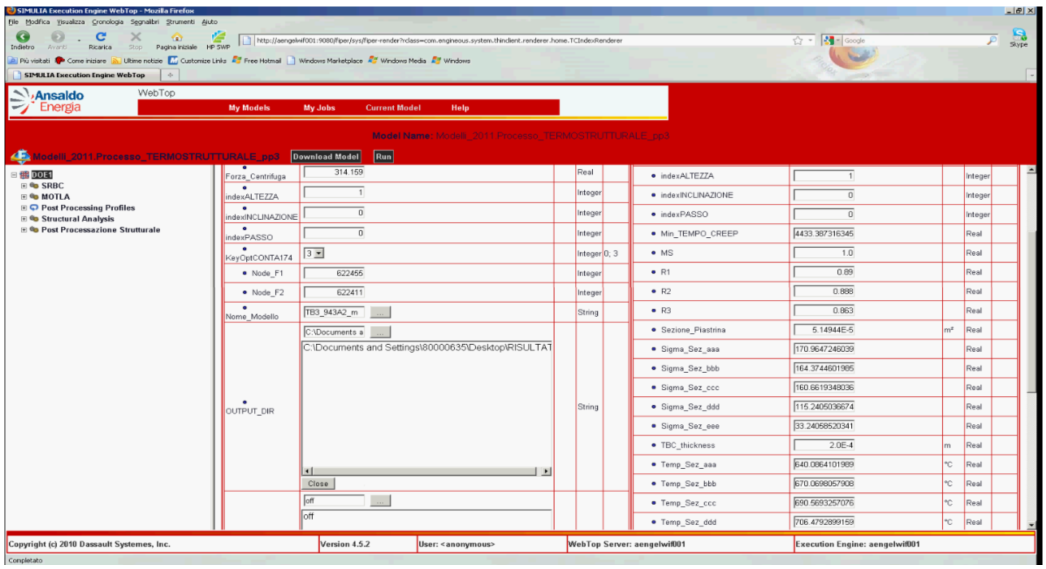


Figure 15. Hole diameters as new parameters for four DOE analyses

5. SEE (formerly Fiper)

This process is implemented in the SIMULIA Execution Engine (SEE) structure. With the use of the SEE, it is possible to share various standard processes through the company's IT resources.

A custom WebTop also has been implemented so that each of Ansaldo Energia's users is able to run and manage the process with the ability to modify input files and parameters directly from the browser.



6. Results

Based on the DOE data mentioned above, we have been able to analyze all the results obtained (temperature maps, maps and trends for stress, and variations of the cooling flow rate) for each configuration to help identify new cooling configurations.

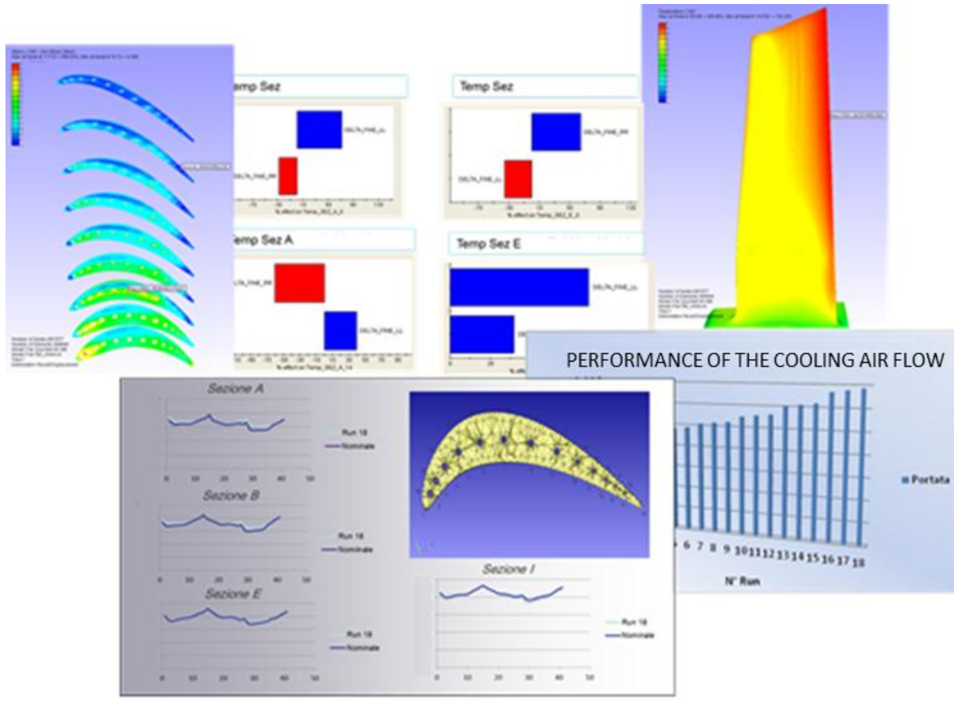


Figure 16. Examples of the results

The results of the first DOE analysis show that a reduction in the number of ribs (up to their total elimination) does not lead to critical conditions in the blade for either creep or fatigue and all the criteria of mechanical integrity are respected. The elimination of ribs causes the temperature to be more homogeneous over the entire blade and the peaks remain unchanged (with the standard configuration that includes ribs in all channels); the flow of cooling air, however, increases.

With the four DOE analyses varying hole diameters, it was possible to find a solution with smooth holes and reduced diameter which is not critical with respect to either creep or fatigue and that also minimizes the cooling flow rate.

7. Conclusion

The innovative aspects of this study can be divided into two different categories: methodological and technical innovations.

The methodology is innovative because the activity has been conducted in a completely multidisciplinary manner, with direct links between parameters of one discipline (heat transfer) and the results of another (mechanical integrity). To create these links two main elements were needed: close cooperation between specialists of different disciplines and a software tool capable of creating a single automated calculation process.

The study was technically innovative because it made it possible to obtain a new solution for the cooling system of the blade that meets all the criteria of mechanical integrity and that also allows simpler and therefore less expensive machining by eliminating ribs, thus improving the cost effectiveness of the design in economic terms. In fact, a solution was found which includes a cooling system without the use of ribs, devices which require more complex processing and special qualifications, and thus raise the manufacturing cost of the blade.

Both the innovative aspects – methodological and technical **-** represent a reduction of costs.

The introduction of this new methodology of integrated and automated design reduces the computation and design time and consequently the development costs, and the new technological solution (i.e. the new cooling system) simplifies the manufacturing process to lower manufacturing costs for each set of blades, thus reducing waste.

It is also important to highlight that the use of the process object of the paper (i.e. a cooled turbine blade) and, more generally, of this type of approach to the design of many gas turbine components, results in significant benefits and improvements both in the processes and in the final product. The main benefits are listed below:

- Sharing know-how
- Management and traceability of the design data
- Standardization of design processes
- Reuse and repeatability of the design process

8. References

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9. Acknowledgments

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