## CASE STUDY // TURBOMACHINERY

# AN INTEGRATED APPROACH FOR OPTIMIZING TURBOMACHINERY DESIGNS

**ANSYS and optiSLang provide a new approach to turbomachinery design by applying numerical simulation and optimization based on objective and reproducible methods.**

## Introduction

Turbomachinery design today primarily relies on the intuition of experienced designers to determine which angle needs to be modified to improve the design. A new integrated approach to turbomachinery design based on objective and reproducible methods will be introduced in this article. It is intended for engineers and require neither mathematical expertise nor many years of experience to be applied. This optimization method is capable of scanning the entire design space in order to survey it completely and to identify local optimums. By this initial step, an algorithm generates more detailed simulations which represent the optimal solution with a high level of accuracy.

## Challenges in turbomachinery design

There are many variables involved in turbomachinery design, each causing a complex effect on the final product performance. Today's most common design methods start with a one-dimensional analysis and include engineering experience to obtain an initial design having a reasonable efficiency level of approximately eighty five percent. The next step is usually a computational fluid dynamics (CFD)

simulation. This provides a more detailed look at the flow velocity as well as direction and pressure conditions. It also identifies issues such as recirculation which cannot be detected with one-dimensional analysis. However, to run such a simulation takes normally a considerable amount of time and each run provides diagnostic information about just one design iteration.

Experienced turbomachinery designers can review CFD simulation results and make educated guesses about which design modification might be possible to generate a significant improvement of product performance. Such designers are capable of increasing efficiency up to almost ninety percent. However, there are just a few engineers having the experience needed to intuitively understand which parameters need to be changed to improve the design.

Even these experts are rarely capable of achieving a 90%+ efficiency level which can be found in today's best-in-class designs. Attaining this level requires a much more sophisticated analytical process. By using CFD, hundreds or even thousands of potential designs can be analyzed automati-

cally. Even with the latest computing hardware, it is still a challenge to deal with the large amount of computing time and resources required to conduct such simulations. Consequently, turbomachinery designers want to address this challenge with optimization algorithms that reduce the number of simulation runs required to explore the design space and to identify the best designs. There are many different optimization algorithms delivered as black box applications which often require considerable mathematical expertise to operate. These algorithms can also fail to find an optimal solution because of limitations in their capacities.

Due to the complexity of turbomachinery development, parameters leading to optimal solutions are often located in spaces surrounded by relatively inefficient designs. Therefore, optimization algorithms that push efficiency towards higher levels often fail to identify the optimal solution, because, while avoiding surrounding low-efficiency designs, they tend to shift temporarily towards design spaces of reduced efficiency.

Another fact making turbomachinery development complicated is that the structural design process must be performed simultaneously in order to ensure the design will be able to handle the resulting loads. Typically, design and structural engineers work in different departments with different tools. Both frequently make design modifications. This might create the risk that the two groups work on different files causing extra expenses and delays in the downstream process.

## Integrated approach

This article will demonstrate an integrated approach for optimizing the design of a centrifugal compressor while ensuring sufficient robustness towards manufacturing variations. The design geometry, including the blades and hub body, was defined in ANSYS BladeModeler, which is fully integrated into the ANSYS Workbench environment. The design was defined in a number of 2-D sketches, either at span-wise positions or at arbitrary user-defined positions. Thus, a full 3-D design was interactively generated providing quantitative information such as blade angles and throat area.

In this application, the geometry of the blades was defined by the meridian flow path consisting of two parametric sketches, one for the hub and another for the shroud. The location of the leading and trailing edges for the rotor, as well as the return guide vane, were defined based on the meridian plane. Angle and thickness distribution of the hub and shroud layer defined the shape of the blades. There were a total of 17 input parameters, as shown in Fig. 1b.
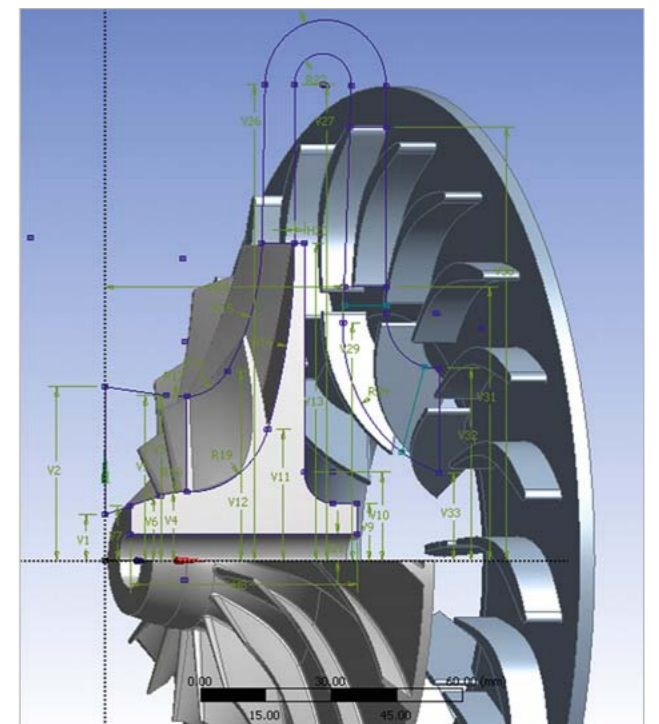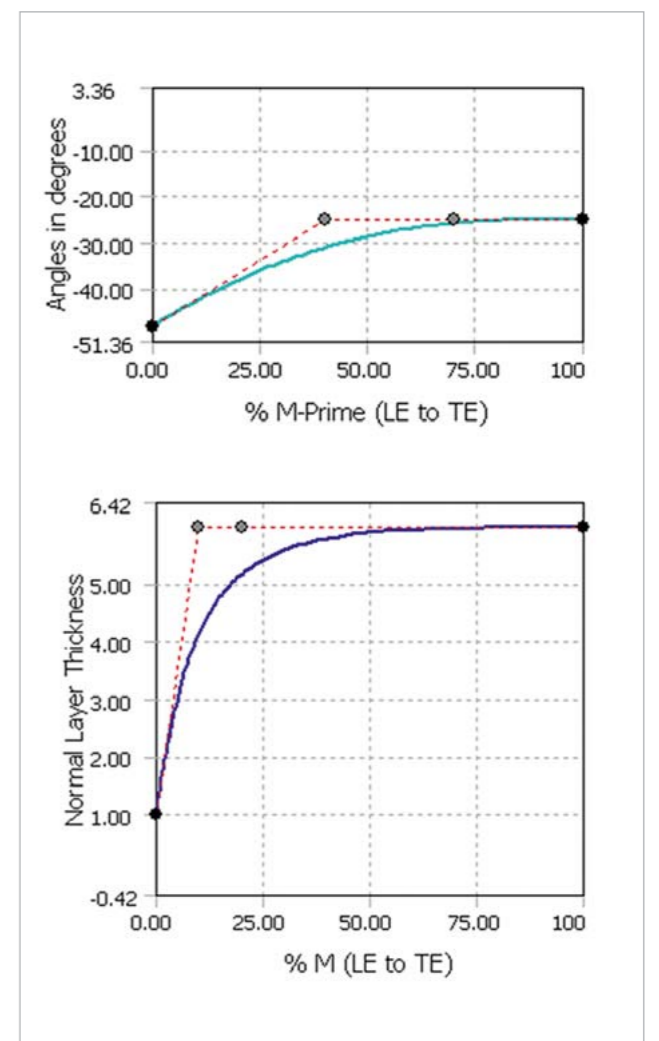


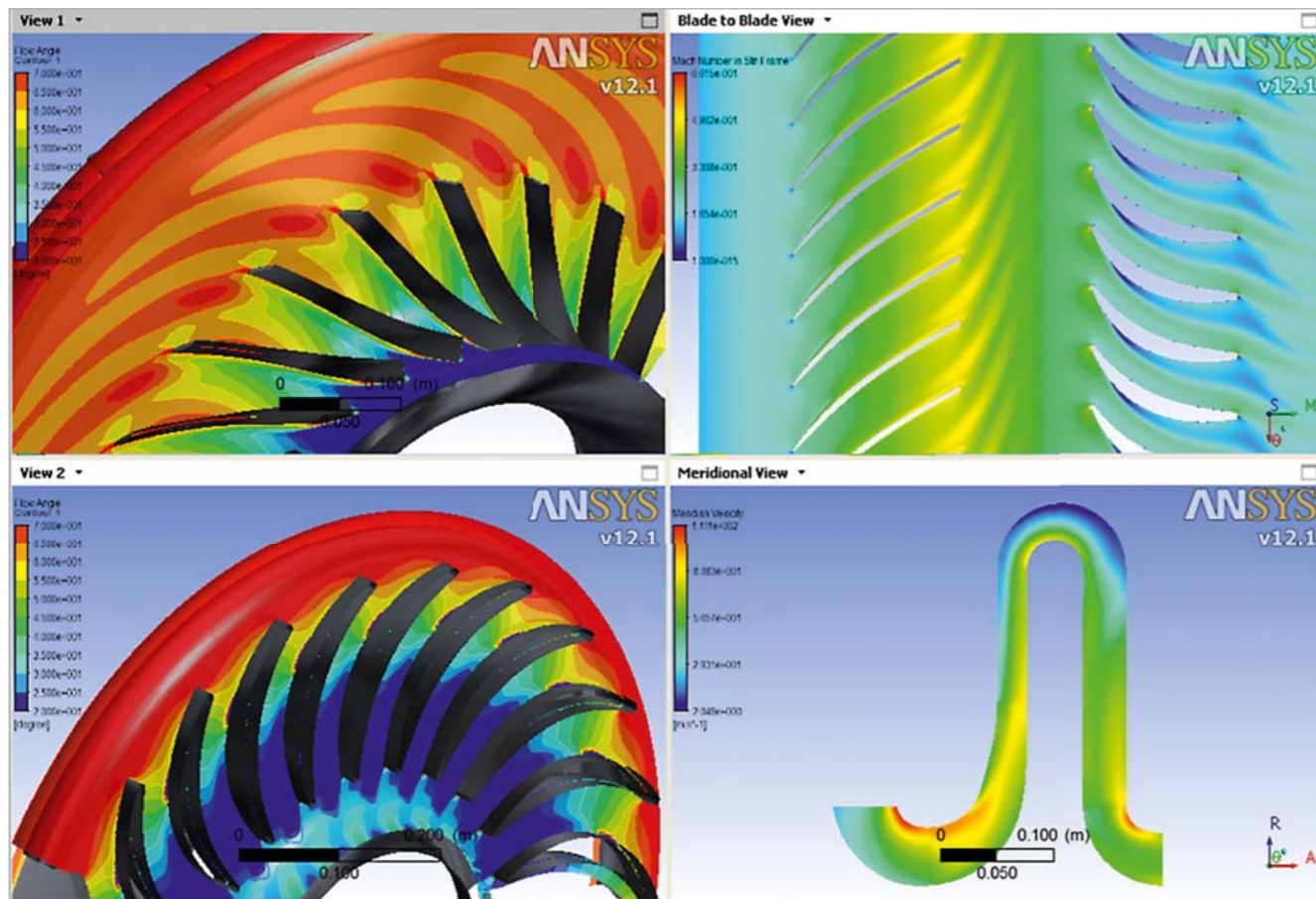Fig. 1a: Parametric geometry



Fig. 1b: Input parameters

Fig. 2: CFD simulation results

## Computational fluid dynamics

A key advantage of the integrated approach is that both the flow and the structural groups work with the same design geometry within the ANSYS Workbench environment. This saves a considerable amount of time by eliminating the need for sending modifications back and forth to enter them into the model. The integration also includes the structural simulation, as well as the flow simulation, into the optimization process. Thus, for example, the optimization can be configured to select the design with the highest efficiency while also considering specific static and dynamic mechanical properties.

Based on the mesh resolution defined by the user, ANSYS TurboGrid was used to automatically generate the mesh for the computational fluid dynamics (CFD) simulation. The model included one passage per component with a profile-transformation rotor-stator interface as well as with chronological periodic interfaces. The total pressure and temperature were defined at the inlet, while the mass flow rate was defined at the outlet. Assuming an ideal gas, ANSYS CFX was then used to solve the model. The output parameters, such as total pressure, temperature ratio and isentropic or polytropic efficiency were determined using CFX-Post. Fig. 2 shows typical simulation results. The transient rotor–stator capability resolved the true transient interaction between components in regard to maximum accuracy. It can be applied to individual pairs of blade passages or to the entire 360-degree machine. Setup and use was as simple as it had been with the other frame-change models. It was also possible to combine transient and steady-state frame change interfaces in one computation. This was complemented by the inclusion of the second-order time differencing, which provided greater transient accuracy. Furthermore, transient blade row (Time- and Fourier transformation) models allowed unequal pitch systems to simulate multi-rows using only a few blade passages and less than the full 360-degree geometry.

## Structural analysis

The mechanical model used one segment of the rotor with cyclic symmetry reducing computational time without any loss of numerical accuracy. The model was fixed at the inner radius. The rotor was loaded by centrifugal force and fluid pressure using results of the CFD simulation. Data handling and fluid-structure coupling were automatically performed in ANSYS Workbench, as shown in Fig. 3. After the completion of the static simulation, a pre-stressed modal analysis was performed. The results of the mechanical simulation included the maximal displacement, von Mises stress and the eigenfrequencies. The design requirements included an upper limit of those stress and eigenvalues that did not match the rotational velocity in order to avoid resonance.
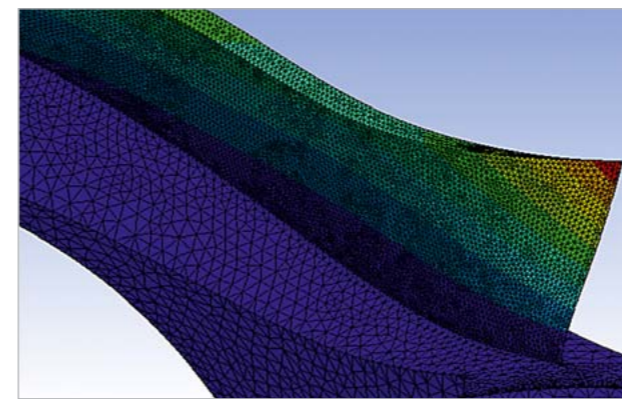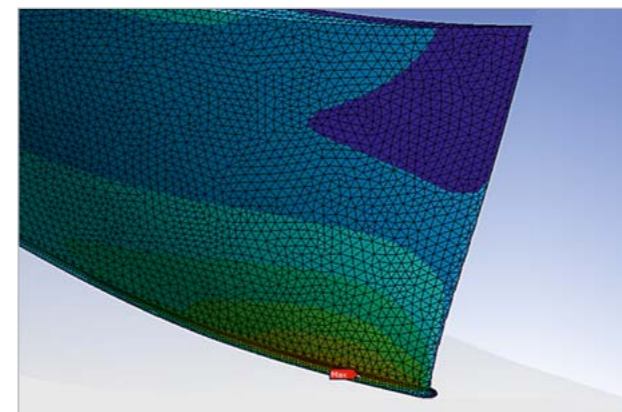
Fig. 3a: Mechanical displacement



Fig. 3b: Mechanical stress

## Sensitivity analysis

With the flow and structural models set up, the next step was to automatically simulate the minimum number of design points needed to map out the complete design space. Thus, not only the design meeting the spec, but also those providing the highest possible level of performance while meeting other constraints, could be confidently identified. The software tool optiSLang was used for sensitivity analysis, optimization, robustness evaluation and reliability analysis. The optiSLang inside ANSYS Workbench integration runs simulations by importing parameters automatically, thus, no additional user input is required.

A sensitivity analysis uses a designed experiment to evaluate the reliability of the numerical model and identifies the most important input parameters. The Metamodel of Optimal Prognosis (MOP) algorithm uses Latin Hypercube Sampling to scan the multidimensional space of the input parameters. A Latin Hypercube is an n-dimensional object representing n different analyzed design parameters where each sample is the only one in its axis-aligned hyperplane. In this case, there were about 50 design parameters and about 100 design points were solved in order to create the MOP. This model represented the original physical problem and enables analyses of various design configurations without any further simulation runs.

The integration platform optiSLang inside ANSYS Workbench provides a seamless data transfer between applications and process controllers that sequentially simulate all of the design points and collate the outputs. Parametric persistence makes it possible to automate the optimization process including file transfer, mapping between physics, boundary conditions, etc. When the user clicks the Update All Design Points button, the first design point, containing the first set of parameter values, is sent to the parameter manager of ANSYS Workbench. There, the design modifications are processed from the CAD system to post-processing. The new design point is simulated and output results are passed to the design point table where they are stored. The process continues until all design points are solved and the design space is defined for later optimization.

optiSLang's Coefficient of Prognosis (CoP) determines whether the metamodel is reliable or not. This calculation also determines which input parameters have a strong influence on the outputs. The response surface graphically depicts the influence of the relevant parameters on the system's performance and shows where the highest efficiency is located. Fig. 4 shows the CoP and the response surface. In this case, the CoP was 84%, which indicated that the model was admissible but still could be optimized. The sensitivity analysis generated an efficiency of above 89% based on relatively rough simulations run parallel on a computing network overnight. This is about the maximum level that a highly experienced designer could expect to achieve within a reasonable time period.

The sensitivity analysis also showed that the eight most significant parameters account for nearly all result variations. This information was used to decisively reduce the time required for the detailed simulation by eliminating the
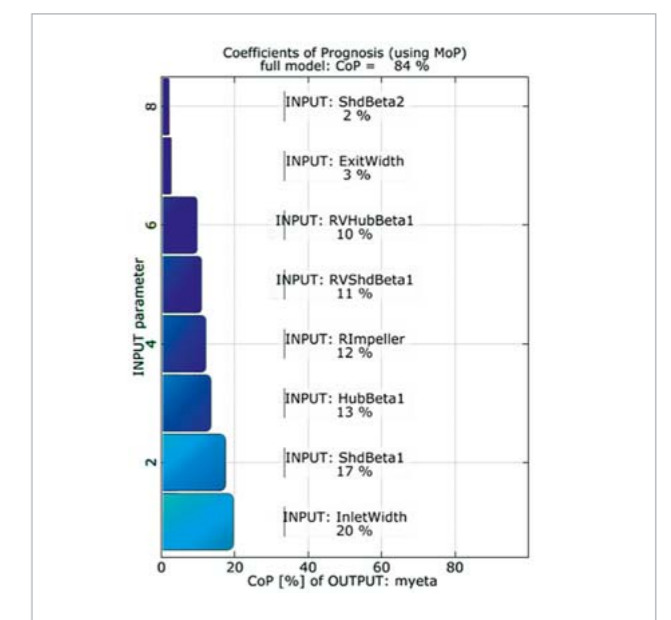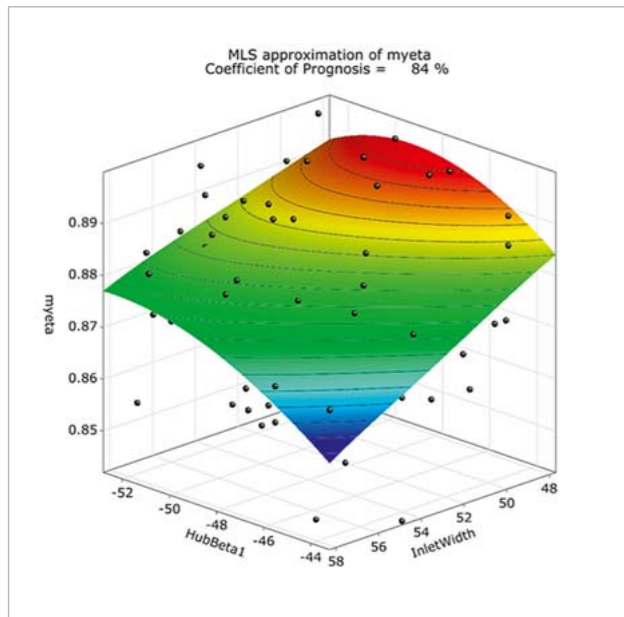


Fig. 4a: Coefficient of Prognosis (CoP)

Fig. 4b: Response surface

variables that do not appear to have a significant impact on the results. For verification, the engineer can also check the numeric model, such as by examining the upper and lower bounds of the design parameters.

## Design optimization

With the entire design space examined and the most promising region selected, the next step was running a more detailed simulation. optiSLang's optimizer provides a wide selection of algorithms. In this case, the sensitivity analysis showed that the practical designs were located in a relatively small area of the design space. The Adaptive Response Surface Method (ARSM) was selected because of its efficiency to generate optimal solution based on starting points that are already in the vicinity of the optimum. If the sensitivity analysis had shown many design space areas containing practical designs, it would have been necessary to choose a different algorithm.

|                  | Initial | SA     | ARSM   | EA     |
|------------------|---------|--------|--------|--------|
| **Pressure Ratio** | 1.3456  | 1.3497 | 1.3479 | 1.3485 |
| **Efficiency [%]** | 86.72   | 89.15  | 90.62  | 90.67  |
| **# Simulations**  | -       | 100    | 105    | 84     |

Table 1: design optimization

The direct optimization with ARSM generated another 1.5% improvement in the efficiency level to 90.62%, which is truly a best-in-class result. This level of efficiency is beyond what could be reached by using manual methods regardless of the designer's experience. With ARSM, approx. 10

simulations can be run parallel resulting in a required time of about three days. Using all parameters, a second optimization was performed with an Evolutionary Algorithm (EA) as a contol point to check whether the elimination of design parameters in the first optimization was appropriate or not. The EA simulation hardly provided any further improvement, confirming that the additional input parameters have a negligible effect on the results.

## Robustness evaluation

So far, the simulation dealt with an idealized setting where, according to the CAD geometry for example a 50 degrees angle is assumed to be exactly 50 degrees. In real world manufacturing, of course, one blade will have an angle of 50.1, the next 49.9 and so on. All of the other design parameters, including material properties, also vary. In order to determine the effect of this variance, we need to design a probability distribution that will simulate the real world manufacturing output. A Gaussian distribution is often used to model manufacturing tolerances while a log normal or Weibull distribution is common for material properties. Again, a Latin Hypercube sampling distribution was used because of its efficient ability to estimate the outputs of a large number of possible designs based on a small sample of actual simulations.
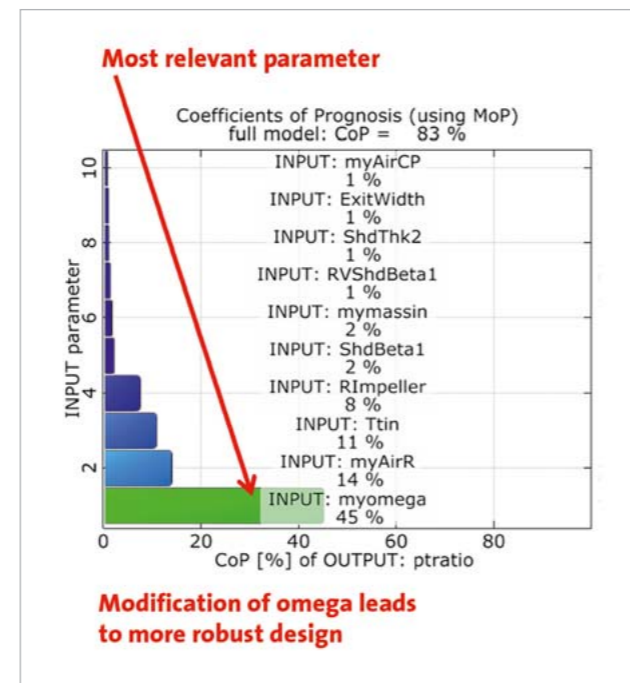


Fig. 5a: CoP of myomega variable

The robustness analysis results showed that an estimated 13% of the manufacturing volume had a pressure ratio outside the limits. The CoP was 83 percent, which indicated that the results are reliable. The robustness analysis indicated that the fluctuation of pressure was primarily caused by the rotational velocity, the so called myomega variable
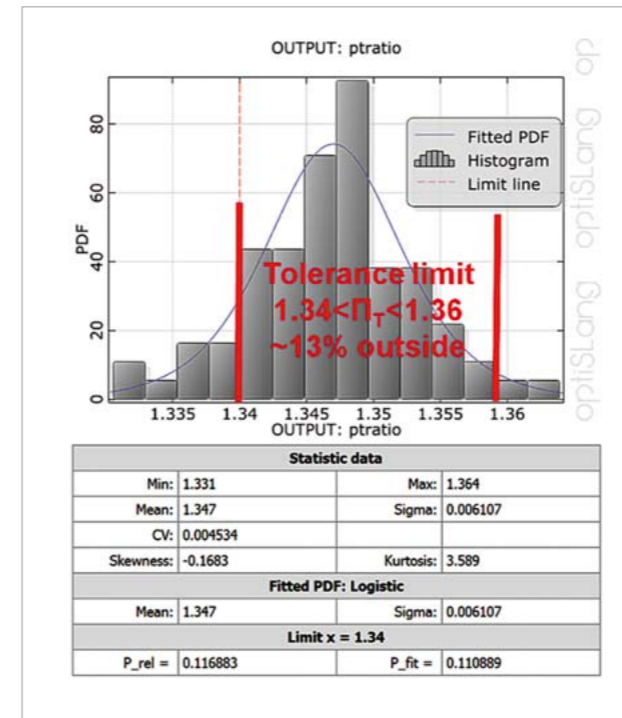


Fig. 5b: Robustness evaluation of pressure ratio

shown in Fig. 5. Controlling this parameter will have a major impact on pressure distribution. It was also worth noting that the pressure ratio was tilted towards the lower limit. Shifting the distribution in the direction of the higher limit will significantly reduce the proportion outside the limits. The other design parameters caused negligible effects which means there might be potential for opening up manufacturing tolerances in order to reduce costs.

## Conclusion

By using the multi-physics platforms ANSYS Workbench and optiSLang, an automated process can be applied to achieve robust design optimization with reproducible methods. The process provides automatic geometry regeneration, high-quality meshing for each possible design, automatic solver execution as well as automatic post-processing. Robust design optimization makes the virtual development process more sophisticated, for example by including the impact of manufacturing variations. The results can be seen in improved product performance and Robustness.

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