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 by 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 automatically. 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.

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.

**Integrated approach**

This case study explicates the ANSYS and optiSLang optimization approach to turbomachinery design by applying numerical simulation and optimization based on objective and reproducible methods.
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 save a considerable amount of time by eliminating the need for remeshing within the ANSYS Workbench environment. This saves a considerable amount of time by eliminating the need for remeshing within the ANSYS Workbench environment.

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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.

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 integrated runs simulations by importing parameters automatically, thus, no additional user input is required.

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.
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 efficient ability to estimate the outputs of a large number of possible designs based on a small sample of actual simulations.

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.

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 control 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.

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.

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 omega variable.