

Simulation Driven Design Enabling Robust Design

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Abstract: The airplane engine business is a highly competitive market and gas turbine engines are at the leading edge of technology development. In recent years, the application of optimization techniques and simulation-driven design during the development of engines has become a standard practice. Using such techniques also shortens the development time for gas turbines and reduces development costs. This in turn helps engine companies remain competitive. In this environment it is increasingly important to look at the performance of the components at the nominal design definition stage, as well as to account for variabilities that may occur during the manufacturing process and use of the products. This has to be done early in the development process to ensure the safe and reliable operation of the components and engine over the complete lifetime and in all operating conditions. The presented paper will discuss the application of automated design processes and robust design techniques for real world development tasks. The basic processes for robust design (define – characterize – optimize – verify) will be explained as well as some of the detailed tools employed in this process. Automated analysis and design processes are setup to allow the effective application of these tools in real-world design tasks for recent gas turbine projects. A view of future trends, including requirements for future software developments, will also be discussed.

Keywords: design optimization, probabilistic design, robust design, response surface methods, design for six sigma, design automation, simulation-driven design, optimization, sensitivity analysis, design of experiment, Monte-Carlo simulation

1. The robust design process

The foundation of design for six sigma (DfSS) is the same throughout the industry; however the roadmap to get to the finished product is very often defined differently (Simon, 2002). Rolls-Royce uses the define, characterize, optimize, and verify methodology (DCOV) to complete robust designs using a design for six sigma approach. This approach helps the engineering community focus on customer requirements, design space exploration, automation, simulation, error proofing and finally verification of the design via a test program. An overview of the key steps and tools is given in Figure 1.

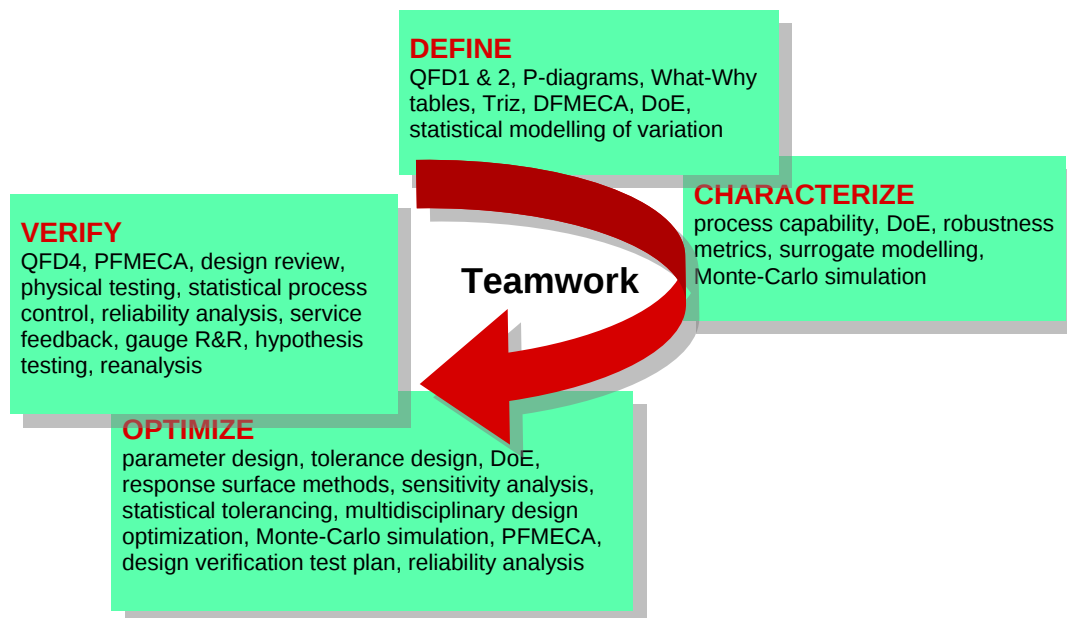


Figure 1. Basic process and key tools for robust design.

The define stage is the backbone of the process and consists of various, classical six sigma tools to choose from and a methodical process to step through depending on the scope of the project the team is working through. The team must deliver the following before proceeding to the next stage:

- Validated customer requirements
- Validated concept
- Nominal design
- Parameter diagram
- What-why table
- Models for input variation

The define stage is very similar to the define, measure, and explore stages of the DMEDI process (Watson-Hemphil, 2004); the identify & design stages of the IDOV methodology (Woodford, 2002) and also the define, measure, analyze, & design stages of the DMADV process. Rolls-Royce takes a deeper dive into the technical aspects of the DfSS approach in an attempt to address as many potential design issues before the product progresses to the testing phase.

The characterize phase addresses the fundamental difference between the classical design approach and the DfSS approach. During this phase the nominal design is assessed from a robustness point of view. It is during this phase of the process that variation in the output is

considered and quantified. The transfer functions $[y=f(x)]$ are developed and the variation data for the inputs, quantified during the design phase, are used to quantify and understand the variation of the output. Understanding the variation is just as important and a more powerful communication tool when describing the design to an audience with a varied knowledge base. Sensitivities, interactions, trends, capability, and probability of conformance to the objectives are typical tools used to communicate this information and exact values are not necessary to understand the challenges and make design and manufacturing decisions. These tools make up the information needed to assess design robustness. The method in which these metrics are achieved is through the use of Monte-Carlo simulation utilizing the transfer functions created by the analysis code or a surrogate model for time intensive code. It is also during this phase of the process that the team looks to utilize automation and simulation-driven design. Automation can become critical if the project involves various analysis packages and complex, long-running code. The multidisciplinary integration of the various analysis and design tasks becomes very important in this phase as a single discipline assessment is no longer fit for purpose. The payback comes in the form of time savings and utilization on future projects running the same automated code. The automated modules and workflows can be reused for similar design tasks and often time savings in the order of 30% can be realized.

Similar to the define phase, the characterize phase has a list of deliverables that need to be addressed before moving to the next phase of the project. These deliverables include the following:

- Robustness metrics for key product characteristics
- Understanding of the most influential design parameters
- Sensitivity information to support design decisions and trade studies
- Satisfactory surrogate model for simulation code
- Confirmation of house of quality information from the define phase by calculations in the characterize phase
- Published surrogate model for use in future designs

The characterize phase goes far beyond a classical design approach. Historically a design was analyzed from a nominal standpoint and during testing, then the product lifecycle variation and probabilities of conformance were understood after the fact. This method is very costly to the business and the customer. At some level this process will continue but it is reduced substantially by addressing as much of the variation up front in the initial stages of the product life cycle. This phase is where sophisticated simulation comes into play to allow the assessment of the designs in the early design phases. Again the trend is to integrate multiple disciplines to get a better picture of the real behavior of the proposed design solution and to allow the assessment of the design solutions against multiple criteria.

The optimize phase does exactly what it implies, optimizing the design solution to achieve the most robust solution that can be realized within the design space. The optimize phase ensures that the design will be robust in meeting all specification requirements when the full range of expected variations occur in component requirements and tolerances. It also ensures that the tolerances chosen are within capability limits of the supply base and manufacturing facilities. Optimization does not include only the performance objectives, but as many of the objectives as possibly which

ultimately drive product costs and in-service costs. Optimizing a design solution for many key product characteristics rather than just the performance objectives is a step change in the product development cycle and will ultimately drive in-service costs lower. This technique becomes essential when dealing with power by the hour contracts and the product needs to stay on wing as long as possible to meet customer expectations and business demands.

The optimize phase deliverables are seen as follows.

- Solution that is robust against part variation and implied and nonimplied customer requirements
- Tolerance settings that simultaneously satisfy robustness and the capability of manufacturing and supply chain
- Models that can be reused in similar designs
- Surrogate models established for the preliminary design process

The final stage of the process is the verify stage. This phase is not utilized as often as the prior stages due to the cost of testing compared to the cost of analysis. One design may go through the three prior stages numerous times before finally being tested. This reiteration is related to the fidelity of the analytical methods and the costs of hardware testing compared to analysis capability costs. The analysis and simulation available today is much more powerful, is less time-intensive, and has improved fidelity compared to the analyses available in the past. Our dependence on empiricism has been reduced. Now we can take advantage of the computer-enabled analytics to create accurate simulations in an effort to reduce hardware tests. However, it should be noted that hardware testing remains critical for certain high complexity situations; but the amount of hardware tests needed now compared to the past are reduced. The verify phase seeks to put together a logical and more focused testing plan based upon information gathered in the prior phases and confirm the assumptions, analysis, and conclusions created in the first three phases.

The verify stage deliverables are identified as follows.

- Confirmation of assumptions from prior stages of the process
- Measured data statistically within predicted values
- In-service data gathering and exploitation strategy
- Report and lessons learned documented for the next projects

Not all process steps are needed in every application. The idea is to generate innovative, timely solutions that meet the needs of the customer.

By completing the steps identified previously, the theory is to get to a design plateau rather than optimal design points. This plateau may not be optimal for some key product characteristics but ultimately it will be the best design when all the product characteristics are considered as illustrated in Figure 2. The left side of Figure 2 shows a traditional approach where the design is optimized for peak performance. However, considering variability in the design inputs the real performance of the design solution is illustrated with the red zone. This zone clearly highlights that some instances of the design perform far superior with respect to the customer requirements but others are not fulfilling the requirements resulting in customer dissatisfaction and complaints. The aim of the robust design process is to find the “plateau” as illustrated in the right hand picture of Figure 2. Here the design inputs show the same variability but the key product characteristic is

far more stable and predictable. This design solution results in a product consistently delivering against the key customer requirements. Selecting such a design solution in turn results in improved customer satisfaction, fewer complaints and overall cost savings during the life cycle of a product.

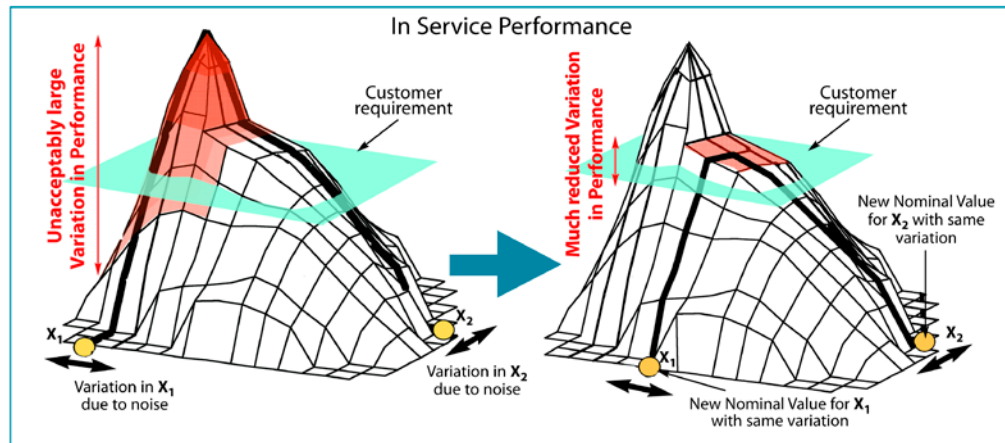


Figure 2. Basic aim of robust design process.

2. Simulation and Automation as part of the Robust Design process

For a widespread application of the previously described basic design process the simulation and analysis tools and capability needs to be adjusted too. Another view on achieving robust design is given in the five steps below:

- Automate process (execute design and analysis processes without human interaction)
- Process integration (build up of integrated processes between various disciplines)
- Design exploration (getting an understanding of the design space characteristic)
- Optimization (achieve the best compromise regarding all requirements)
- Robust design (make sure that the design performs for variable conditions)

The first two steps in this sequence are in the areas of automation and process integration tools. The last three steps are covered by six sigma methods. However, for the widespread application of these methods the automated and integrated simulation and design processes need to be enabled by supporting software tools. Tools like Isight (Simulia Web site, 2009) allow the integration of multiple analysis and simulation tools and packages into consistent and repeatable workflows. The required cross discipline and business integration can be facilitated via systems like Fiper (Simulia

Web site, 2009). After the processes are automated and integrated, the six sigma methods like design of experiment, response surface modeling, Monte-Carlo simulation and six sigma assessments can be easily applied in a seamless software environment. The use of such commercial solutions allows Rolls-Royce to focus on the core business of developing gas turbines.

However, considerable training is required to allow the effective application of these methods in real-world applications. The users need to understand the advantages and even more the disadvantages of the various methods and tools to select the correct method for the task in hand. Also it is important to understand why the automated systems and optimizations have arrived at the suggested solutions and designs. It is not acceptable to just accept a solution proposed by the simulation and design optimization without understanding why this is a “good” solution. Hence, Rolls-Royce has implemented a simulation-driven design process which has a large “human” content as shown in Figure 3.

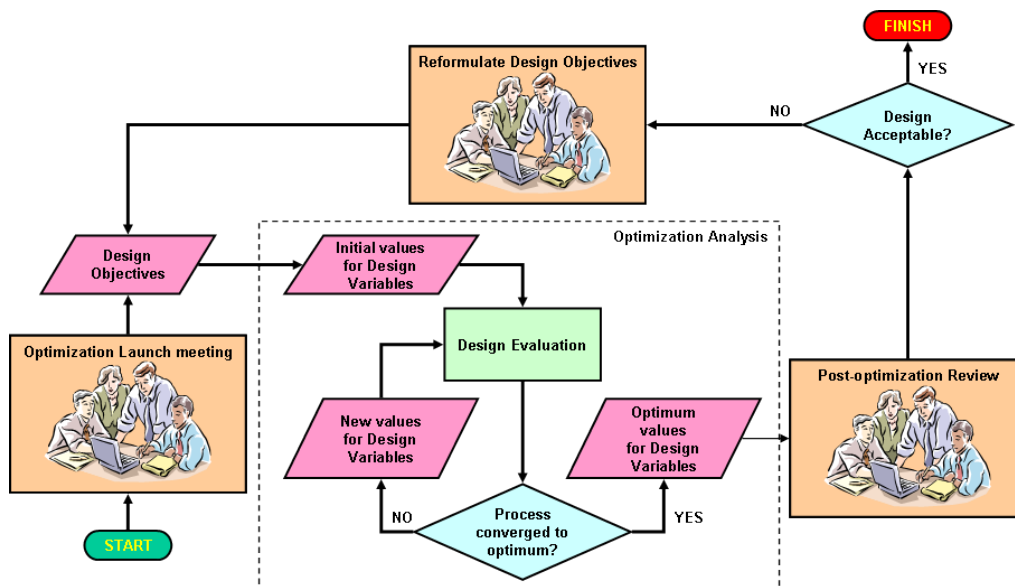


Figure 3. The simulation-driven design process.

This process contains various design reviews and assessment meetings to guide the optimization and analysis process. The final design is always selected by the design team. The automated and integrated design and analysis process provides the input to the team. Using these automated processes trade curves of various key product characteristics can be presented instead of the single analysis results in the non-automated areas. This additional information allows the design team to

assess the proposed design solutions in a much more thorough way than was possible a few years ago. This enhanced assessment process also reduces the risk of the engine development programs early in the design phase. The cross-discipline integration of the automated simulation processes also allows a multicriteria decision making process as now various key product characteristics can be assessed against each other in an effective way.

Another huge benefit of the automated design and simulation processes are the achieved efficiency gains. Typically at least 30% improvement can be achieved via automation of the design and analysis processes. The main driver here is the streamlined data transfer as highlighted in Figure 4.

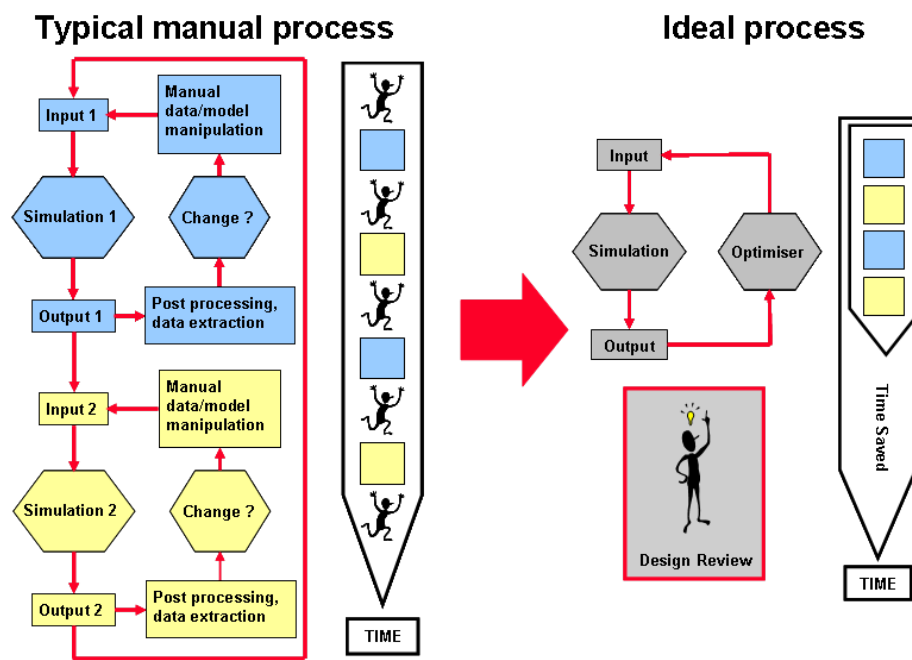


Figure 4. Benefit of process automation.

In a manual design or analysis process, the data is assessed in a manual way. The required changes to the simulation or design are then implemented in a manual way and require many manual data transfers. These tasks are all time consuming and error prone. The automated simulation and analysis process also acts as a standardization of the design and analysis work and hence the consistency of the results is increased. The modeling style, meshing, etc. is no longer dependent on how the respective analyst implemented the solution.

To develop such automated design and analysis tasks an integrated team of process specialists, software experts and six sigma experts are put together to derive the best way of automating the

task at hand. The engineering process is mapped and analyzed. In conjunction with the discipline specialists, an ideal process is derived and implemented. This implementation takes into account the available time for the design and analysis tasks as well as the available computing capacity. This work is done on the production jobs with the support of a dedicated department. The process is then piloted and, if successful, implemented as the global standard for this type of work. Via this building block approach, immediate benefits can be realized. Over time the whole design and analysis process can be automated in such a way via manageable smaller tasks and tested sub-processes.

3. Case studies

This section shows several applications of all or part of the process and tools described in section 1 and 2 for real development tasks during the gas turbine engine development. The three case studies show the application for component level, subsystem and system level tasks highlighting that the described approach can be used from system to detailed component work. In addition the examples span the development process from preliminary design to assessment of the detailed design and manufacturing variability. Since 2001 the main toolkit to do such activities within Rolls-Royce has been the Isight software system.

3.1 Robustness assessment of a compressor disk

The first case study is describing an assessment of the robustness of a compressor disk with respect to the manufacturing variability. For this work a single compressor disk was modeled in the Rolls-Royce thermo-mechanical analysis package and temperatures, stresses and movements of the component were calculated. The geometry was modeled in the CAD system and transferred into the analysis package via neutral files so that the analysis or the CAD package could be changed with minimal effort.

During the define phase of the DCOV process manufacturing data was collected. The effect of the manufacturing variability on the key outputs (disk weight, stresses at critical locations and movements on critical locations) was assessed using a classical Monte-Carlo method. The inputs (design variables) for this assessment were the key dimensions of the part. To decrease the time required to obtain a result a response surface methodology was employed. For this methodology a space filling set of analysis was performed via a Latin Hypercube design of experiment covering the whole range of the design variables. Based on this data set a so-called response surface was constructed and validated. This response surface could be either a simple polynomial representation or a more complex Kriging or Radial Basis function model. Using this response surface, the calculation time was reduced from hours to minutes and thus a Monte-Carlo simulation was now in reach of the design team.

For the design variables, normal distributions were assumed with the manufacturing capability obtained from the manufacturing area set at a ± 3 sigma level as shown in Figure 5 for selected design variables. It is important to emphasize that the parametric CAD model needs to be capable of representing the manufacturing variability. Sometimes this task requires a separate model as the parametric model used for assessing design changes may not be suitable for the investigation of manufacturing variability. The Monte-Carlo simulation process samples these input distributions

and calculates the temperatures, stresses and movements for a given set of inputs. This process is repeated several hundred times until the variability of the key output characteristics are sufficiently quantified. Typically a descriptive sampling scheme is employed to improve the accuracy of the quantification of the output distributions with fewer simulation runs. This descriptive sampling scheme puts more emphasis into the tails of the input distribution and hence a better quantification of the output variability can be achieved with fewer calculations.

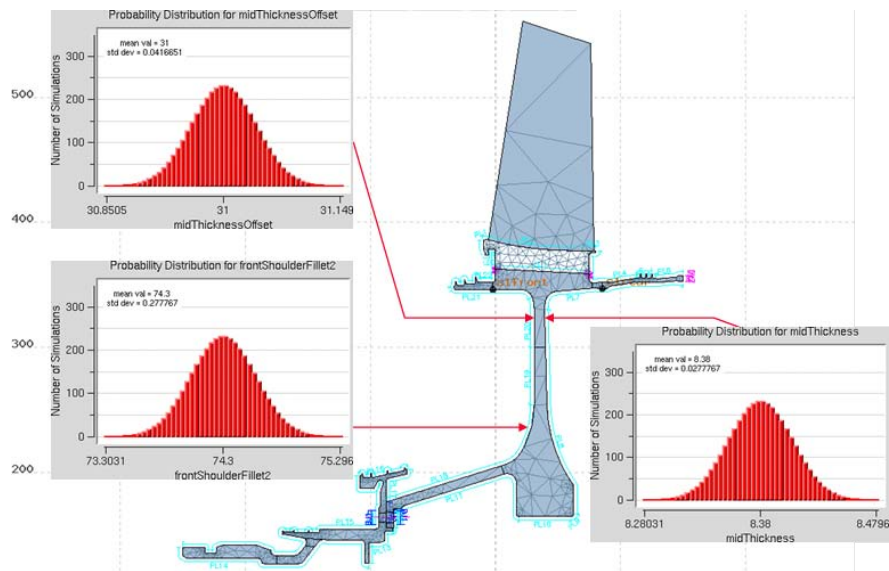


Figure 5. Typical distributions for the design variables.

Figure 6 shows two typical results of such a calculation for the disk weight and the movement of the seal arm in radial direction. Using the Monte-Carlo simulation technique a lot of information can be gained for the quantification of the key output parameters: mean value, standard deviation and the shape of the distribution. In the given example both output quantities have a normal distribution with a small standard deviation. Using this additional information gained via the Monte-Carlo simulation the design team could assess the design option in a much better way. The assessment could include the variation of the outputs and not just the nominal value. For example, using the radial movement from the example the design team could assess if under all considered circumstances the seal is not clashing with the static part. The variability of the disk weight could be rolled up in to the subsystem and system weight variability and so a more accurate weight prediction of an engine is possible.

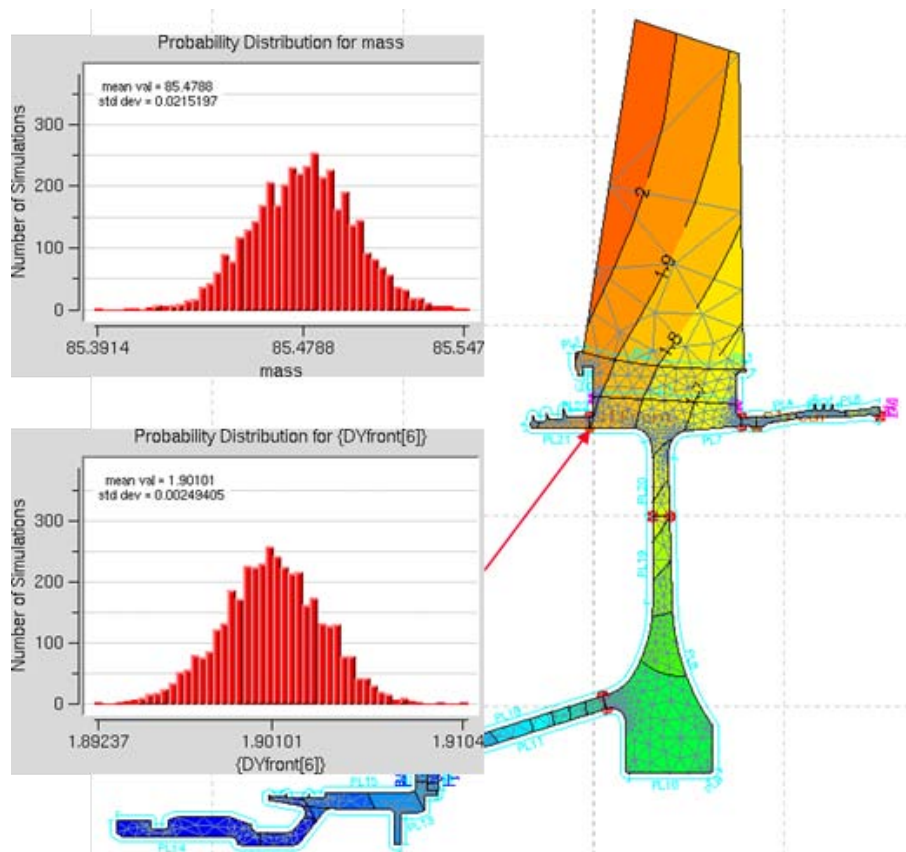


Figure 6. Typical distributions for key output parameters like disk weight and seal arm movements.

3.2 Design exploration and sensitivity studies for a turbine subsystem

The second case study is based on a training example which is used to demonstrate the benefits of automated simulations and introduce the users to the basics of optimization and sensitivity studies. A simplified turbine subsystem was used to achieve running times compatible with a training environment. However, all the key features of a modern turbine subsystem were represented. The design variables and the constraints for the problem are given in Figure 7. The thermal model represented a case cooling system for tip clearance control, different cooling mass flows as well as different heat transfer assumptions. In addition to these design variables the ingested mass flow into the sealing cavity could be varied. The constraints for the problem were liner temperatures and temperature gradients across various structures. The gradients were limited in order to limit the

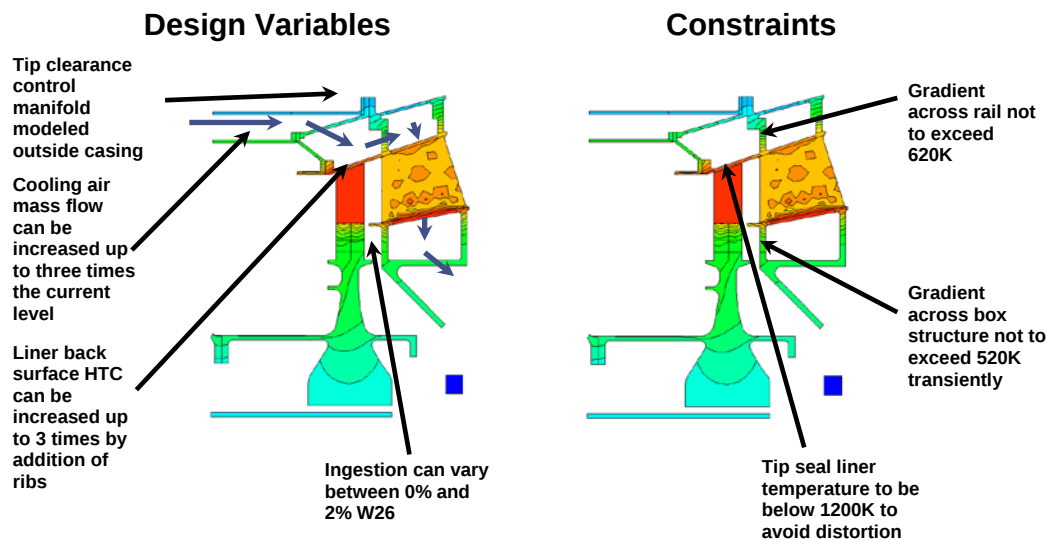


Figure 7. Setup of training example to demonstrate application of design exploration and sensitivity studies for a turbine subsystem.

thermally induced stresses and strains. The key objective for the example was the tip clearance of the system as this is a key driver for the turbine subsystem efficiency.

The whole problem was integrated into the process automation tool and several automatic simulations were performed. As outlined earlier the first step in the process was a thorough design space exploration. The behavior of the design to changes in the key design variables was analyzed with the help of Pareto plots, main effect plots and interaction plots. A design of experiment scheme was used to sample the design space. Based on the results of the design of experiment runs a response surface was constructed which in turn was then used to derive the key influence factors. Selected results are given in Figure 8 for the liner temperature GRTLINER and the temperature gradient across the box structure GRDELTA2. Using the second order response surface the main effect plots and interaction plots contain curved lines, which is in contrast to the classical description of these methods where only linear effects are modeled. Using the data from these plots two key influence factors and their interaction were identified for the liner temperature. All the other factors modeled in this example had no influence on this output variable. On the other hand for the temperature gradient across the box structure all modeled variables showed some effect. After the basic behavior of the design was understood an optimization was performed. In this case an overall tip clearance measure was chosen as the objective. Looking at the plots on the right of Figure 8 it can be seen that the OVERALL figure of merit (middle plot) was decreased and that the value of the temperature gradient across the rail GRDELTA1 was increased until the predetermined constraint was reached.

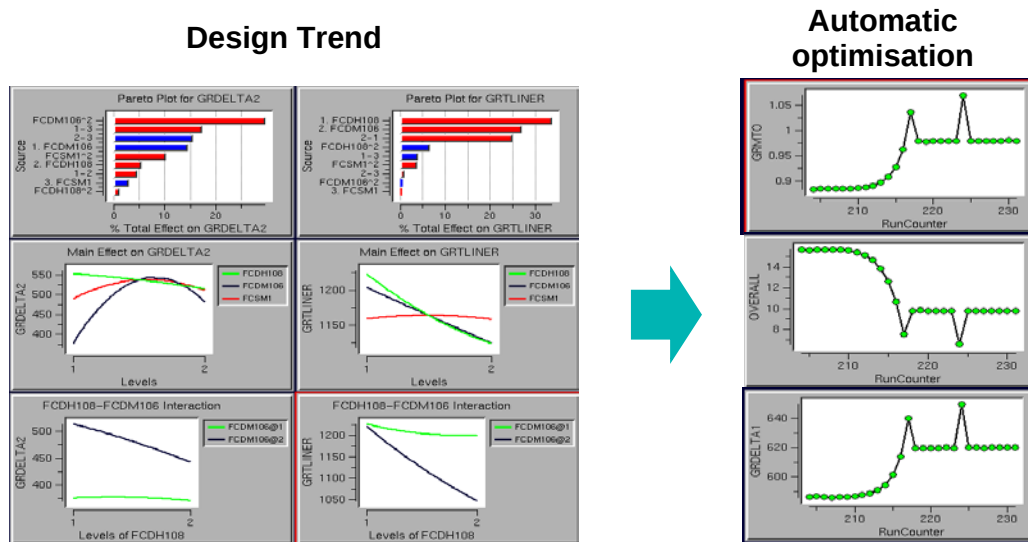


Figure 8. Sample results from the training example.

Using this simple example several key principles of automation, design exploration and optimization can be explained to the users during the training. In addition, the users get some practice with using the toolset and principles for problems which are close to the real world topics they will encounter during their work.

3.3 Whole engine cycle optimization

The final case study was chosen to highlight the benefit of cross-functional integration and automation to support concept decisions in the early phases of an engine development project. During this phase of a development project, the main system decisions are made influencing the key product characteristics. To support these activities a multidisciplinary team was assembled to conduct the preliminary design using simplified methods to assess the key systems of a gas turbine. In the presented case, the team was assembled with combustor, turbine and performance specialists. A supporting tool was generated to close all the iterative loops in the performance calculation, e.g. effect of cooling flows and efficiency effect. The overall process and the key data exchange flows are shown in Figure 9. The basic performance data such as key cycle temperatures, pressures and mass flows were transferred into a combustion tool which calculates the emissions and also the temperature distribution at the entry to the turbine. These temperatures in connection with the basic performance data were used in a turbine cooling prediction tool to estimate the required cooling flows to achieve the required life of the turbine components. Finally the basic performance data was also used to predict the expected efficiency of the turbine module. As highlighted, several of the data flows were going back to the performance module and hence an

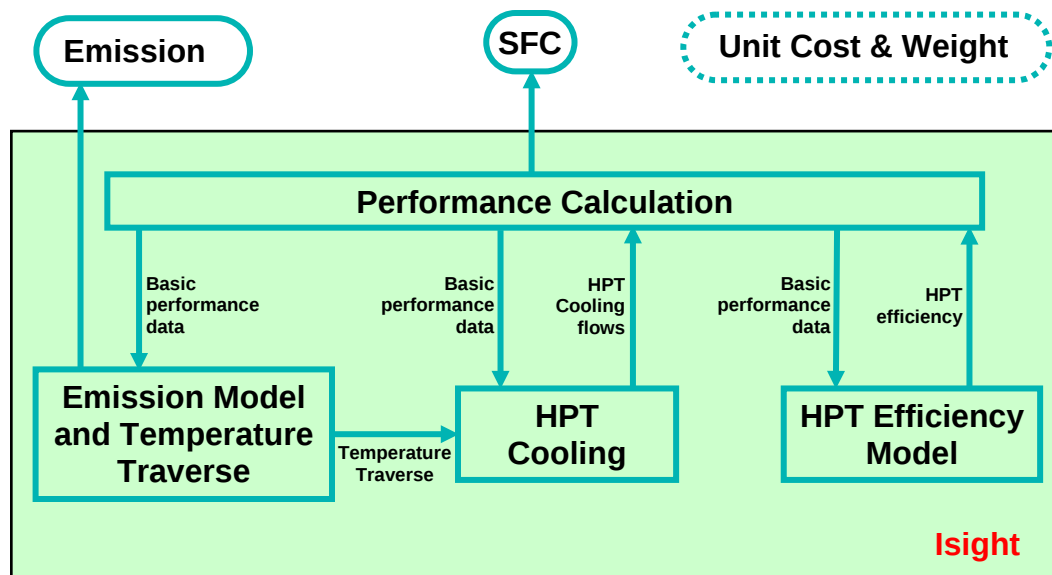


Figure 9. Multidisciplinary analysis process to support the preliminary design phase of an engine development project.

iterative solution was implemented to arrive at a consistent set of performance data, turbine cooling and turbine efficiency numbers. The performance module then provided a specific fuel consumption number (SFC) for the engine. SFC is a very important figure of merit for the overall engine assessment. The key question posed to the team was to identify the ideal turbine entry temperature for the given boundary conditions. In the next step, the unit cost and weight of the module and engine will be included into this assessment.

Several design options for the turbine blades as well as several settings for the turbine entry temperature (SOT) were investigated. Sample results are given in Figure 10 showing the effect of SOT on the SFC and high pressure turbine (HPT) cooling flows. Interestingly a considerable increase in design SOT does not really improve the SFC value. The only marked improvement in the SFC value can be seen via changes in the shroud style of the turbine blades. This is contrary to the assumption that higher cycle temperatures (higher design SOT values) will improve the efficiency (SFC value) of the engine. The reason for this behavior becomes clear if the graph on the right of Figure 10 is taken into account. Here it can be observed that due to the higher temperatures more cooling air is required in the turbine to achieve the required life of the turbine components. As this turbine cooling air is taken from the compressor it has a parasitic effect on the overall engine efficiency. In the presented case, all the benefits of the thermodynamic efficiency gains were used up by the negative effect of the cooling flow increase and hence no overall effect on engine efficiency (SFC value) was observed. In this case the only way of achieving a better engine efficiency is different shroud options with different cooling requirements. This behavior has been known in principle for a long time. However, the tools and

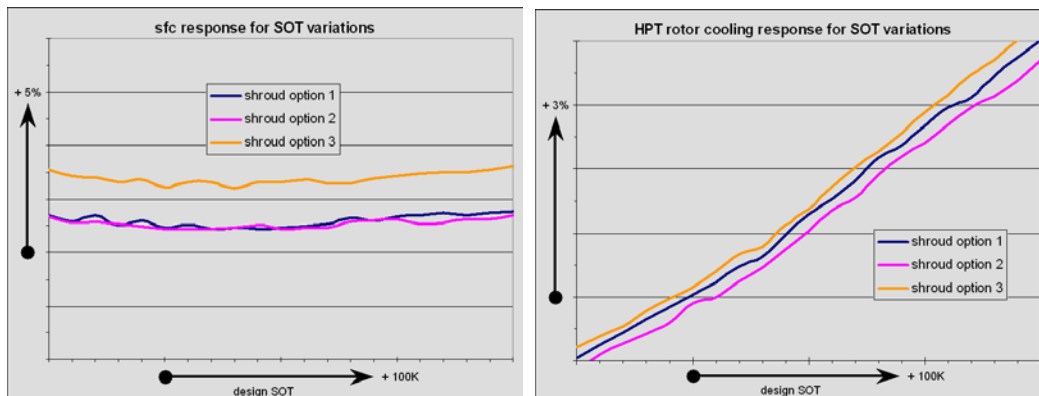


Figure 10. Engine efficiency (SFC) and HPT cooling flows for a given variation in the design turbine entry temperature (design SOT).

the multidisciplinary integration allowed a quantification of the effect. This detailed analysis allowed the cross-functional team to make data driven decisions based on a multitude of analyzed design concepts instead of having to rely on experience. In addition, converged and consistent sets of performance data and high pressure turbine assumptions have been used which would have not been possible without an integrated and automated tool.

As a side effect of this work a more team-oriented work environment which allowed a much more efficient communication between the various areas involved in the preliminary design of an engine was created. To build the tool all the key experts were consulted and several drawbacks of the manual processes were eliminated. The new process is now available as a standard way of performing such an analysis and hence the analysis quality as well as the reaction time for new assessments has been improved.

4. Conclusion and Future Requirements

The basic principles of the design for six sigma process have been discussed together with the key tools of the define – characterize – optimize – verify process employed within Rolls-Royce as the backbone for the DfSS work. For an effective application of these methodologies automated and integrated simulation and analysis processes are required. The basics step and guidelines for such an automation and integration have been discussed. Several case studies highlighting key issues and benefits of this approach have been presented. The case studies range from component to full system assessments.

It has been demonstrated that the automated and integrated simulation and analysis tasks can be used to greatly improve the effectiveness of the design process and at the same time the quality of the obtained results and decisions can be improved. The automated processes also serve as an

effective way of introducing standardized workflows into the analysis and simulation areas of the company.

It is anticipated that this area of process integration and automation will be growing in the next few years. Further developments and improvements in the available integration and optimization tools will support this trend. It is important that the software is usable by the final user and not just by specialized methods and tool development areas. Also a tight integration of key tools (CAD, FEA, cost, postprocessing, meshing, statistics, etc.) used in industry would be beneficial. Finally the integration with the emerging simulation data management tools is a key development area. This integration would extend the principles currently used in the geometry world (data storage, versioning, workflows, etc.) into the analysis and simulation world and would be a huge benefit for industry applications. This kind of control of the analysis and simulation data and processes is a key requirement in the drive to migrate to simulation driven certification processes.

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