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DIGITIZING AMERICAN MANUFACTURING

DMDII FINAL PROJECT REPORT

Integrated Design and Manufacturing Models with Metrology	
Project Team Lead	**Rolls-Royce Corporation**
Project Designation	DMDII 14-08-01
UI LABS Contract Number	**0220160003**
Project Participants	**National Center of Supercomputing Applications (NCSA)** **Southwest Research Institute (SwRI)** **3D Systems** **Georgia Institute of Technology (ASDL)** **Pennsylvania State University (ARL)** **Microsoft Corporation**
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1 EXECUTIVE SUMMARY

Currently, engineering design and manufacturing face three long standing challenges:

- Manufacturing processes result in manufacturing variation from "ideal design", but expect the actual performance of the part to match the nominal predictions without visibility to the affects these variations have on the performance of the part.

- Holding manufacturing to tight tolerances can keep the part from drifting too far from its "ideal design", but holding all features to tight tolerances increase manufacturing cost even though not all design features are critical to performance.

- Design and manufacturing engineers currently work in silos. Design is primarily performance driven and manufacturing is primarily cost driven. Both cost and performance are vital to keeping a competitive advantage, but there is little visibility to how these two interact with one another.

The DMDII 14-08-01 project successfully developed a methodology that can produce a quantitative comparison between cost and performance while understanding how the manufacturing process affects the performance variation of the part and the sensitivities of cost based on feature-based analysis. This project accomplished its goals by performing the following:

- Developed a "digital twin" framework which analyzed the relationships between parts geometry, performance, and cost to enable an optimal design between performance and cost to meet a customer's needs. The ability to use advanced analytics to understand the variations associated with geometry, performance, and cost enables an improvement in products performance/reliability, reduce costs, and improve engineering productivity. This framework is pervasive for other part families including the as-used conditions.

- Created a system that converts a 3D scan point cloud into a workable format that can be analyzed by structural and aerodynamic performance. This system has improved efficiency by replacing a manual process that takes hours to complete with an automated process that takes a few minutes to complete.

- Produced a single thread workflow that automates the performance analysis in order to predict performance results in a lightweight format that can be used on a per part basis (piece part) or in an in depth trend study (batch of parts). This removes the need for additional resources which are typically required to update performance models for each scan.

- Developed a feature based "should-be" costing analysis that can predict the sensitivity of the part's cost based on the manufacturing tolerances. This innovation is paramount to the development of the cost vs. performance analysis. By creating a link between the performance driven by certain features and the cost of the part (previously defined by surfaces) allows for a direct comparison between cost and performance.

- Automated the process with HPC and DMC capabilities in order to bridge the gap between manufacturing and design by allowing easy access of performance and cost data through hand held devices. By giving easy access to the data produced by this methodology, design and manufacturing will find common ground by having visibility to how the parts are being produced and affects this has on both performance and cost. This will enable further innovations and a better form of communication to develop an optimal product.

This methodology was developed by using one specific application (3rd stage turbine blade), but the framework (Figure 1) can be applied to a number of other applications. By implementing this through the DMC it allows for greater collaboration between DMDII members and facilitates automated analysis to be shared between many different users.

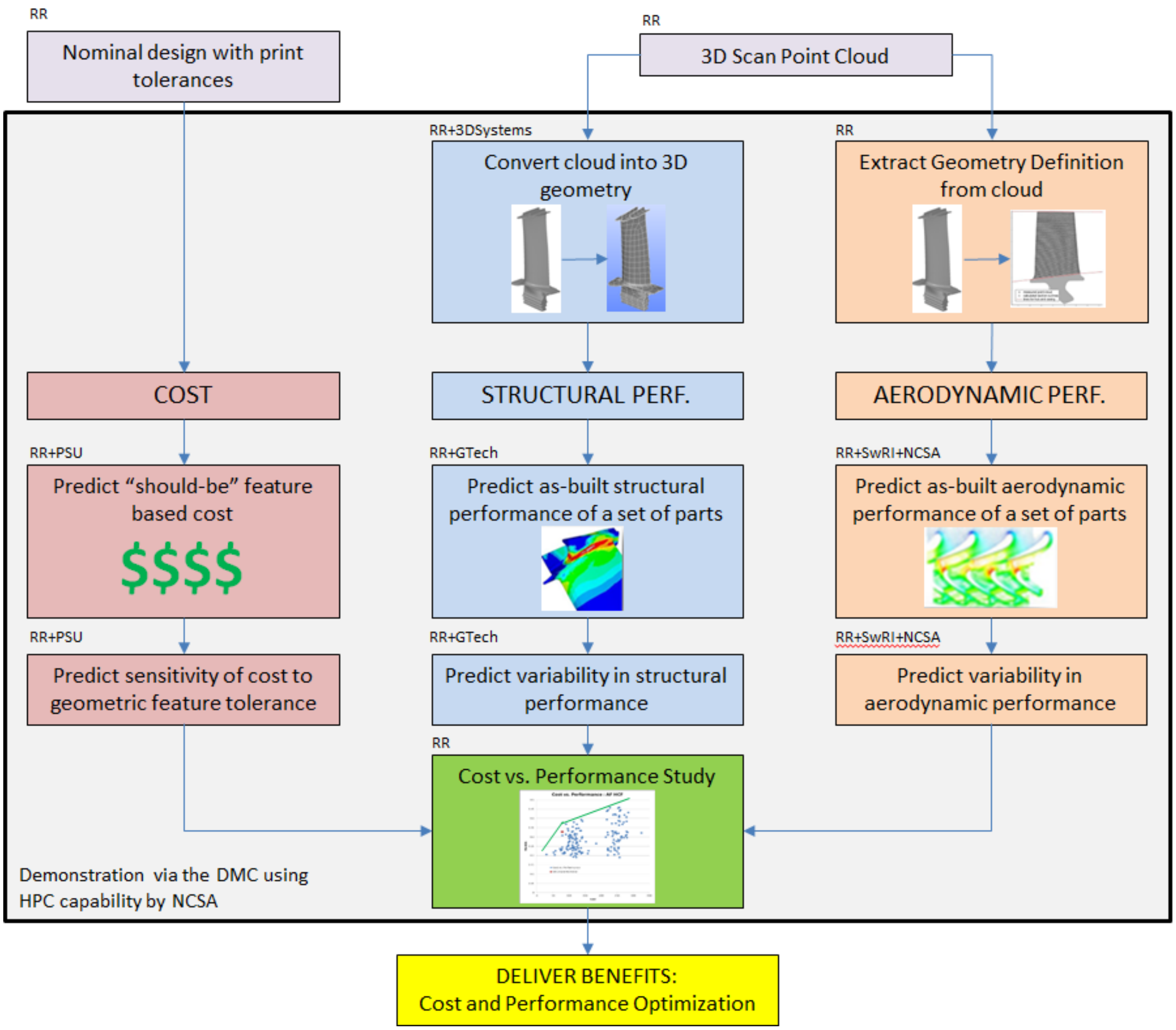


Figure 1. DMDII 14-08-01 methodology overview

2 PROJECT REVIEW

2.1 Project Scope and Objectives

The idea behind this project is that advanced analysis can significantly:

- Improve product performance/reliability
- Reduce costs
- Improve engineering productivity

For this to happen, the software and methods/ technologies, most of which are used today with minimal links between manufacturing and design, need to be tightly integrated to enable a greater degree of information transfer and collaboration between engineering disciplines – design, analysis, and manufacturing.

This project tackles the following persistent problems in the current product design and manufacturing chain:

- Disconnect between manufacturing and design – what is the shape of a part coming out of a manufacturing process, how does it compare to the design intent, and what can we learn about the manufacturing process from the actual shape of the parts?
- Analysis based on the nominal design (geometry, material properties, etc.) with little or no reference to the “as-manufactured” state
- Focus on the nominal performance of components and systems with little or no understanding of how as manufactured shape affects in-service performance. Little or no information on how the performance varies around the nominal due to variations in geometry, material properties and operating conditions
- Focus only on the performance (goal of design engineers), or only the cost (goal of manufacturing engineers) with little or no understanding of how the two are interrelated and can impact the life cycle cost of a product

The DMDII 14-08-01 project had four primary objectives:

- Develop a digital thread based methodology to predict the actual performance (structural and aerodynamic) of manufactured parts and quantify performance variation
- Develop a methodology to understand the impact of geometric tolerance on manufacturing costs
- Establish a link between performance and cost sensitivities of geometric features to enable cost vs. performance tradeoff studies.

- Provide easy access to data generated throughout the product life cycle to design, analysis and manufacturing engineers based on a specific application of the methodology created by this project.

2.2 Technical Approach and Planned Benefits

In order to accomplish the primary objectives of this project, the team applied the following advanced analysis technologies to deliver benefits across the supply chain:

- Advanced geometry data manipulation and conversion software
- Advanced probabilistic and uncertainty quantification algorithms and software
- Advanced "should-cost" modeling methods, databases and software
- Advanced structural and aerodynamic analysis methods and software, along with analysis automation software on high performance computing (HPC) systems
- Advanced computer hardware technologies such as mobile display devices with links to the digital highway

These technologies were used to create a set of tools applied to a specific configuration of 3rd stage turbine blades. Though the tools were developed for a specific application, the methodology demonstrated can be carried over to other components.

In order to complete the objects set for this project, seven technical tasks were required as follows:

1. Capture geometry of as-manufactured parts in a form that is suitable for structural and aerodynamic analysis
2. Predict as-manufactured aerodynamic performance
3. Analyze variation in aerodynamic performance
4. Predict as-manufactured structural performance
5. Analyze variation in structural performance
6. Evaluate impact on manufacturing costs
7. Integrate advanced analysis tools onto the DMC to demonstrate capability

The benefits that are created by this project's methodology are as follows:

- Reduced cost of production and cost of ownership by leveraging knowledge from true manufacturing variability and process capability.
- Integration of HPC and data analytics to enable impact assessments of as-manufactured variability on component performance, maintenance, and integrity.

- Breaking down barriers across the supply chain by having secure (ITAR compliant) transfer of data between manufacturing and design via the DMC and HPC capabilities.

- Access to manufacturing variation on performance and cost allow for enhanced productivity that will allow for tradeoffs and creating an optimal design for the customer.

- Technological advancement and automation created by this project will guide further innovations to better educate the next generation of workforce.

These benefits are critical to the competitiveness of the U.S. industry and can be applied to multiple components and industries.

The Work Breakdown Structure (WBS) is shown in Table 1 along with the designation for each partner's contribution during this project's execution.

Table 1. WBS for the DMDII 14-08-01 project with partner participation.

	Advanced Analysis WBS	RR	NCSA	Georgia Tech	SwRI	Microsoft	PSU-ARL	3D Systems
Task #		P-primary S- support C-consulting						
1	***Project Management***	P	S	S	S	S	S	S
2	***Capture Geometry of as Manufactured Parts***							
	Scan a number parts into point clouds	P						
	Generate blade definition files from point cloud	P						
	Generate 3D CAD models using scanned data	P						S
3	***Predict As Built Aerodynamic Performance***							
	Mesh nominal model for CFD analysis	P	S					
	Analyze nominal aerodynamic performance	P	S					
	Analyze performance of a subset of as built blades	P						
	Compare as built performance to nominal	P	S					
	Post process results	P	S					
4	***Predict Variation in Aerodynamic Performance***							
	Perform probabilistic analysis on scanned geometry	P						
	Use a sampling technique to generate perturbed geometries	S			P			
	Perturb nominal mesh to match generated geometry	R						
	Analyze performance of multiple as built parts	S	P					
	Analyze variation in performance and generate PDFs and sensitivities	P	S					
5	***Predict As Built Structural Performance***							
	Mesh nominal geometry	P						
	Analyze nominal performance	P						
	Develop workflow to mesh selected set of as made models	S		P				
	Analyze performance of a set of as built geometries	C	S	P				
	Review results from as built geometries	S		P				
	Compare as built performance to nominal	P		S				
6	***Predict Variation in Structural Performance***							
	Develop automated workflow with parametric geometry or morph mesh	S		P				
	Perform probabilistic analysis on structural related dimensions			P	S			
	Analyze variation in performance and generate PDFs and sensitivities			P	S			
7	***Evaluate Impact on Manufacturing Cost***							
	Calculate impact on manufacturing cost	C					P	
	Do a cost vs. performance benefit analysis	P					S	
8	***Demo AA work on DMC hosted at NCSA***							
	Set up an instance of DMC on NCSA servers	C	P			S		
	Enable visualization of data via a hand held display device on the shop floor	C	P			C		
	Demo advanced analytics work	S	P	S	C	C	S	C

2.3 Project Team

The DMDII 14-08-01 project was performed by the following members:

- Rolls-Royce Corporation: Team Lead
- 3D Systems: 3D scan to solid conversion
- Southwest Research Institute: Probabilistic analysis on aerodynamic performance
- ASDL at Georgia Institute of Technology: Structural performance analysis and statistics
- Penn State ARL: Costing analysis and statistics
- NCSA: HPC capabilities and DMC integration

3 PROJECT RESULTS

The methodology created by this project was generated by applying it to a specific application. The methodology creates a framework for many other applications that will drive optimized designs that meets both cost and performance requirements.

The primary outcomes from this methodology and its development are as follows:

- With the use of 3D Systems Geomagic Suite, creating an automated system to capture the 3D geometry of an as-manufactured part that can be used in performance analysis.
    - Prior to DMDII 14-08-01: Previously this process was done manually which requires resources to convert each scan component. Therefore, performing this analysis in a production or validation environment is impractical because the manual process can take anywhere from a few days to more than a month (depending on the components complexity).
    - Result of DMDII 14-08-01: Once the system is in place it can be completed in a matter of minutes automatically. This specific application of this process took approximately 2-3 months to create because of a few lessons learned, but could be accomplished in as little as one month with experience. Therefore, it will take more upfront resources, but once the system is in place it eliminates the continuous requirement for resources and saves time by only taking a few minutes to convert (instead of days/months).
- Automated processes for aerodynamic and structural performance analysis on as-manufactured parts.
    - Prior to DMDII 14-08-01: Typically analyzing an as-manufactured part requires stress and aerodynamic analysts to review the .stl file and modify

their analysis to either represent the as-manufactured parts geometry or create a new analytical model for that part specifically. This requires addition time and resources every time an as-manufacturing geometry needs to be analyzed. Therefore, this is impractical for production or validation purposes because of the time and money investment it entails.

  - Result of DMDII 14-08-01: Once an automated workflow is created and properly vetted for accuracy, it can be run without additional resources or adjustments. This will allow for this form of analysis to be used quickly and without continuous analyst resources, which results in time and cost savings, as well as allow for analyst time to be spent on other tasks. Additionally, by making an automated process it enables the ability to determine the performance variation of the manufacturing process, previously not possible.

- Feature-based costing analysis

  - Prior to DMDII 14-08-01: Tools and methods developed in the DARPA AVM project only had costing capability on surfaces which is not easily comparable to performance features.

  - Result of DMDII 14-08-01: With feature-based costing, having a direct cost vs. performance comparison is made possible. Since performance capability is typically dependent on features (shroud width, airfoil height, etc), a feature based costing analysis capability is crucial to drive a direct comparison. Because of this project, a feature-based costing analysis is shown to be possible.

- Manage manufacturing variation based on manufacturing variation in performance and cost

  - Prior to DMDII 14-08-01: None.

  - Result of DMDII 14-08-01: By the use of automated performance and costing analysis, a study can be performed to analyze cost and performance tradeoffs that will enable a more manufacturable cost effective design, while still maintaining the required performance.

- Integration with HPC and DMC resources

  - Prior to DMDII 14-08-01: Manufacturing and design had limited accessibility to running performance analysis without certain licenses or resources.

  - Result of DMDII 14-08-01: Access to analysis in a timely manner without additional resources or licenses. Improves communication by allowing manufacturing and design to communicate through easily accessible data that affects both cost (manufacturing’s primary concern) and performance (design’s primary concern).

4 DEVELOPMENT OF THE METHODOLOGY

4.1 Capture Geometry of As-Manufactured Parts

The objective of this task was to convert scanned 3D geometry data of turbine blades into other formats suitable for aerodynamic and structural analysis. Creating a process of generating consistent 3D CAD models is central to performing static and dynamic analysis on engineering components and systems. Currently, this process is done manually for each individual component which is time intensive and costly process. The outcomes of this project were to provide opportunities for efficiency improvements to allow for this conversion to be implemented in a timelier manner. The conversion method for the aerodynamic analysis was performed using Rolls-Royce in-house software (this will be discussed further in 4.2) and conversion for the structural analysis was performed using 3D Systems Geomagic Suite. Other “scan to CAD” software is currently available on the market and should be capable of doing similar operations to the steps described in this section.

The process began by pulling 100 3rd stage turbine blades from stores and blue light scanning the parts individually using ATOS scanning equipment. ATOS scanning equipment was used in the development of this project, but the same capability is present in other similar blue light scanning equipment. The blue light scanning process captures the external surfaces of the 100 blades and converts them into a .stl file using GOM Inspect software. The .stl file is a point cloud digital 3D image that is primarily used for inspection purposes. Once the blades were converted to a 3D point cloud, 3D Systems’ application engineering team came to Rolls-Royce to conduct an on-site training for their Geomagic Suite. During this training it was determined to most appropriate tools to be used were 3D Systems’ software called “Control” and “Wrap”. These tools converted the .stl by maintaining near net shape of the blade surfaces using NURBS (Non-Uniformed Rational Basis Spline) or patched surfaces which output a parasolid that can be used in analysis. This conversion to near net shape solids has relatively small error (within .0005”) depending on the NURB density defined by the user. 3D Systems developed an automated process specific to the 3rd stage turbine blade used in this project to perform the following tasks:

- Control Software
    - Orients the component by locating against the assembly datum structure on the nominal CAD model, creating an ‘aligned’ 3D geometry.
    - Sends generated “aligned” model to Wrap Software.

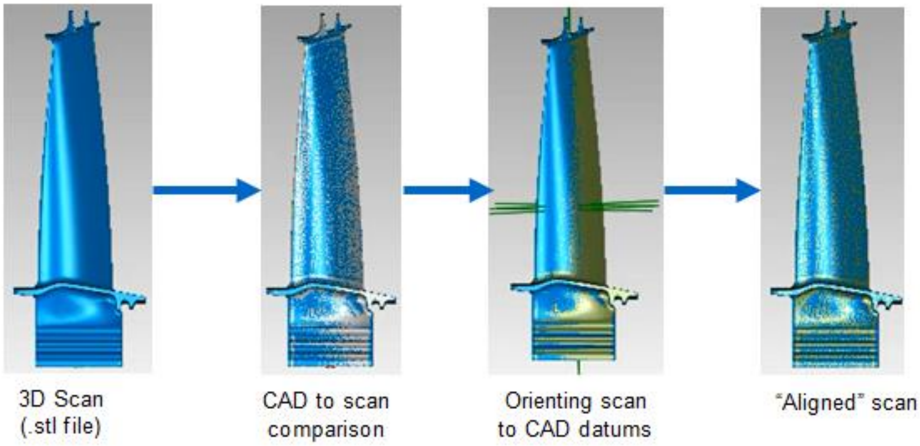


Figure 2. Geomagic Control script process #1

- Wrap Software
  - Opens a watertight NURBS solid (specific template for turbine blade) that constructs a grid around the 3D scanned component.
  - From the NURBS template it fits onto the "aligned" geometry and links to the 3D scan to create an "autosurfaced" geometry.
  - Sends generated "autosurfaced" geometry to Control Software.

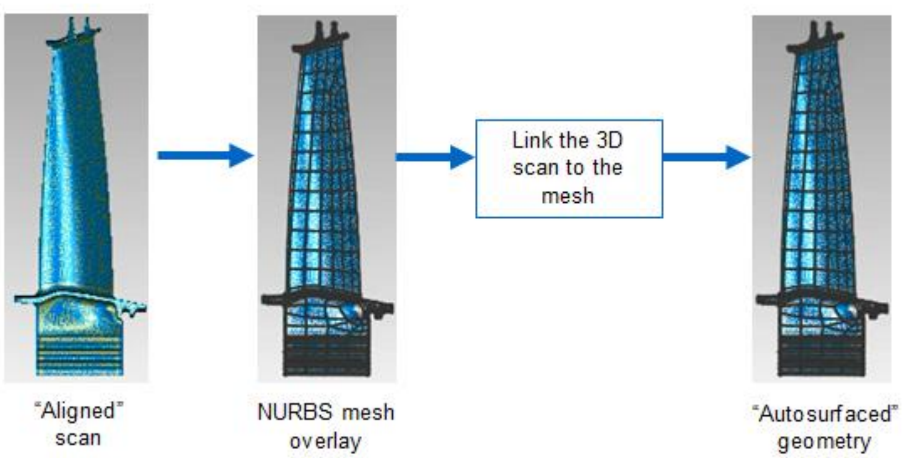


Figure 3. Geomagic Wrap script process

- Control Software
  - Opens the "autosurfaced" geometry and does a quality comparison to a defined tolerance and converts the "autosurfaced" geometry into a workable solid .igs file.
  - This step outputs the .igs file that will be used to structural analysis and a report describing the quality of the new file.

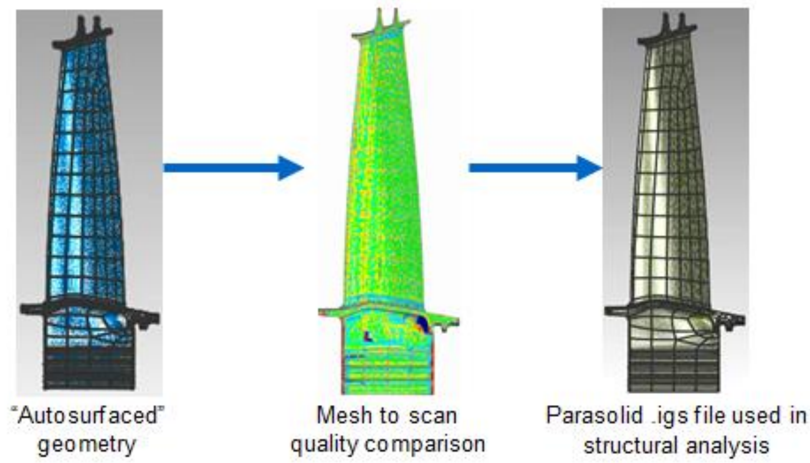


Figure 4. Geomagic Control script process #2

Using this automated process, 3D Systems converted the set of 100 blades into parasolids (.igs files) and submitted them to Georgia Tech to perform its structural analysis.

The automated process developed by 3D Systems and using their Geomagic Suite successfully took an as-manufacturing 3D point cloud geometry of a turbine blade and converted it into a workable solid. This conversion not only allows for structural analysis to be performed, but it also was automated and turned an 8+ hour manual task into a process that only takes approximately 7 minutes. This boost of efficiency and rapid conversion is crucial in the ability to use this methodology by manufacturers and shop floor personnel that will use this in real time. With the use of 3D Systems Geomagic Suite, this template and method can be created for any kind of component and will allow for rapid conversion between 3D scan to a workable solid.

4.2 Predicting As-Manufactured Aerodynamic Performance and Variation

There were two primary focuses with this task. First, was to develop an automated process of taking 3D scanned geometry of 100 turbine blades and running aerodynamic analysis on the component to predict the as-manufactured aerodynamics (flow capacity and turbine efficiency). Second, was to analyze the variation of aerodynamic performance based on a selection of parts scanned and create a surrogate model to explore the design space for the cost vs. performance study. The aerodynamic analysis was primarily done by Rolls-Royce, using Roll-Royce proprietary software, and the probabilistic analysis was done primarily by Southwest Research Institute.

4.2.1 Predicting As-Manufactured Aerodynamic Performance

The first task involved creating an automated process for the as-manufactured blade geometry scans to perform the aerodynamic analysis. The overall system architecture of this process is shown in Figure 5.

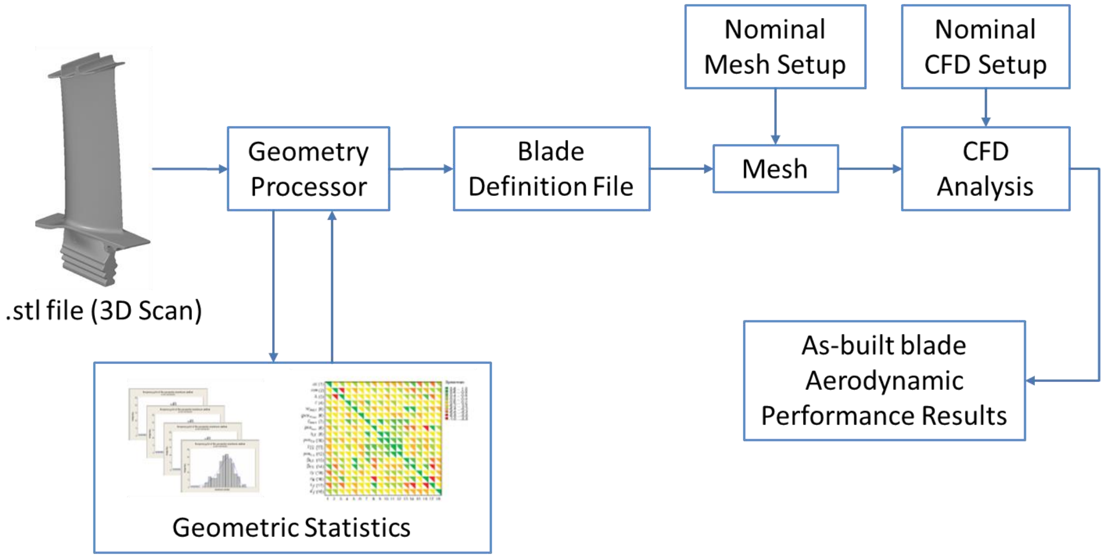


Figure 5. Aerodynamic analysis system architecture

4.2.1.1 Automation of the Aerodynamic Analysis

In order to automate this system, a nominal computational fluid dynamics (CFD) analytical model needed to be created. This model consisted of the following steps:

- Geometry creation – created from the nominal CAD design
- Meshing
- Setting of boundary conditions – applying temperatures, pressures, and constraints
- Submitting CFD analysis
- Post-processing – extraction of performance values

For the demonstration of the procedure in this project, an established Rolls-Royce procedure was used based on in-house, proprietary CFD software. Other CFD software should be capable of performing the steps described within this section as well.

Prior to this project, there had never been an as-manufactured application of taking a 3D scanned model (.stl file) and applying its geometry to the nominal Computational Fluid Dynamics (CFD) analysis. The application of this conversion from 3D scan to a blade definition file was new development of this project. This conversion is a pre-processing geometry handler that takes an STL of a scanned part and converts it into a format suited for input into the existing CFD procedure. The geometry handler starts by inputting the 3D scan and determines the bounds of the airfoil (platform to tip/shroud) and slices the airfoil into many different cross sections. Once the airfoil is cut into cross sections it performs two key steps that were crucial for the automation and development of the surrogate model to analyze the variation of the as-manufactured parts.

1. Creates a point cloud of each of the cross sections in order to properly define the airfoil in a specialized format (blade definition file) that can be analyzed by the CFD analytical model.

    a. This portion of the geometry processor is all that is required for predicting as-manufactured aerodynamic performance, but in order to analyze the variation step 2 is required.

2. Analyzes the geometry of the airfoil at each cross section and measures key airfoil parameters for CFD analysis. These parameters include: leading edge radius, chord length, and lean which are typical parameters that are used by designers to design turbine airfoils. These parameters are directly pulled from the 3D scan to fully define the blades geometry and were used in in the analysis described in section 4.2.2.

Due to the large set of 100 scanned blades, this project required a very large overall number of CFD simulations. Typically, a CFD analysis project will focus on one or a small number of geometric variations. Handling such a large number of geometries in a practical amount of time required the development of an automated process. This process needed to be able to start from a scanned STL file, clean up the geometry, create a mesh, setup the simulation, run the simulation and post-process the results. Existing automation scripts were extended to handle the STL files and clean up the geometry as well as run the simulations on iForge, the high performance computer (HPC) cluster provided by NCSA for this project. Because of the large number of real geometries that the automated process needed to handle, great care was taken to make sure it was robust to changes in the geometry, particularly in the meshing step. This automated process eases not only the work for this project, but for future efforts to analyze this blade and can easily be modified for other similar parts, so continued analysis of manufacturing variation will be as impactful as possible. The process for this project was automated with Python.

4.2.1.2 Analyzing the 100 blades

Once an automated workflow was generated (Figure 5), an extension of the aerodynamic analysis procedure can be used to determine the performance of an entire turbine row, not just a single turbine blade. Turbine rows are made up of an annulus of approximately 80 blades each contributing to the overall efficiency and flow capacity. Analyzers haven't before considered the effects of manufacturing variation, where each blade in the annulus is a little different, and how these variations interact with neighboring blades. In this project, a procedure was created to determine the effects of manufacturing variation on the aerodynamic performance of a full annulus turbine row.

Performing a single CFD simulation of a full annulus of approximately 80 different blades is very computationally expensive. Determining statistical parameters, average and variance, of the performance variation requires a large number of separate CFD simulations. So it's impractical due to computational costs to performance a statistical analysis with full annulus CFD. A less computationally expensive approach was required.

The approach here was to use a series of multi-passage simulations; one passage, two passages, four passages and eight passages; and establish a trend that can extrapolated to full annulus. The one passage case is the standard setup use in the procedure described above to determine the performance of a single scanned part. Only one scanned blade is used. The two passages case uses two different scanned blades together in a single simulation in a partial annulus arrangement. Figure 6 shows a representation of the domain used for the simulations with periodic boundaries on the top and bottom. Four and eight passages cases are like the two passages case but with more scanned blades. The idea is that the more blades used the closer to the full annulus the case becomes, with the goal of reaching a predictable behavior without requiring running any full annulus cases.

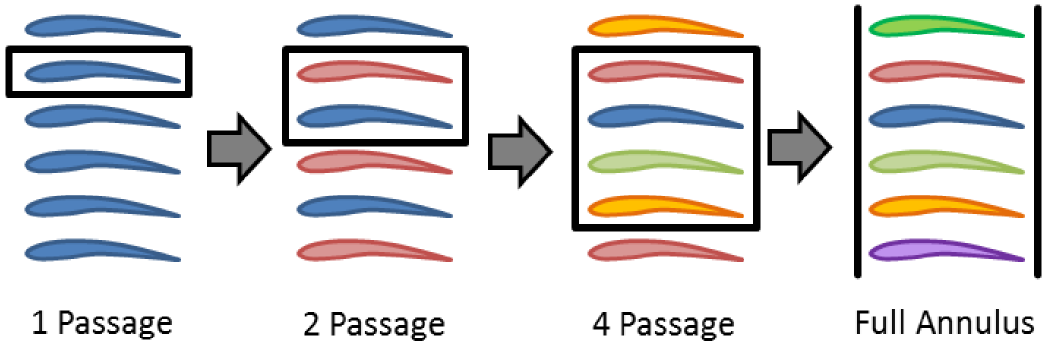


Figure 6. Flow domains for single and multi-passage CFD analysis

The statistical properties of the full annulus row performance are the primary interest in aerodynamic analysis, namely the average and the variance. So the average and variance of the performance of one passage, two passages, four passages and eight passages were first calculated. To determine these values a set of 100 one passage cases were run, 60 two passage cases, 45 four passage cases and 30 eight passage cases. The one passage cases used the set of 100 blades scanned for this project. For each of the two passages cases, two blades from the set of 100 were randomly chosen. The same is done for the four and eight passages cases. Due to the larger domain required for the larger number of passages, the CFD simulation times were two, four and eight times for the multi-passage cases than for the single passage case. Histograms of the results for these cases are shown in Figure 7 with blue, red, green and purple lines for the one, two, four and eight passages cases respectively.

The histograms for the corrected flow show that the average performance, represented by the location of the peak of the curve, is independent of the number of blades used. The variance, represented by the width of the curve, decreases with the more blades used. In fact, the ratio of the variance of the multi-passage cases with respect to the single passage cases is equal to 1/N where N is the number of passages. This tells us that the average flow capacity for the full annulus cases is equal to the average of the single passage cases. Also, the variance of the full annulus cases is equal to the variance of the single passage cases divided by the number of blades. So, a statistical description of the flow capacity variation of a turbine row due to manufacturing variation can be understood by performing CFD on a set of individual scanned blades without ever running a full annulus simulation.

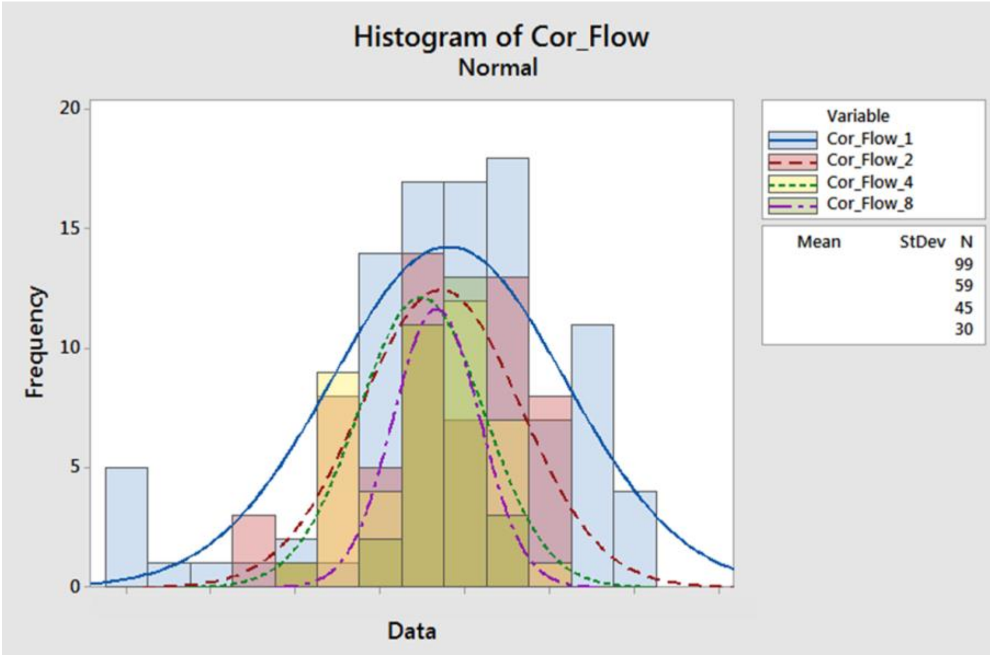


Figure 7. Histograms of Flow Capacity for 1, 2, 4 and 8 passage cases

The histograms for the efficiency, shown in Figure 8, show the same relationship for variance as for flow capacity. However, there is a shift in the average between the one passage and two passages cases. The average for the four and eight passages cases is approximately the same as for the two passages cases. This tells us that a statistical description of the efficiency variation of a turbine row due to manufacturing variation can be understood by performing a set of two passages CFD cases. This also tells us that there is an efficiency loss due to blade to blade interaction that shows up when neighboring blades have different geometries due to manufacturing variation. Also, this interaction is negligible beyond the nearest neighboring blade, otherwise a shift in the average would be seen between two and four passages cases.

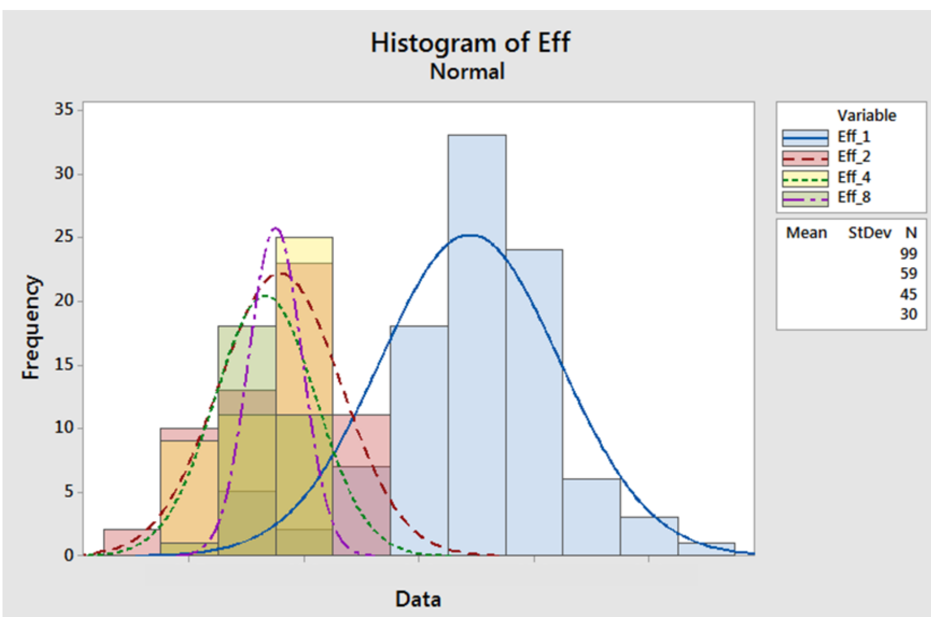


Figure 8. Histograms of Efficiency for 1, 2, 4 and 8 passage cases

The procedure for the multi-passage analysis described in this section provides a computationally inexpensive method for determining aerodynamic performance variation of a turbine row due to manufacturing variation of the turbine blades. New insights were obtained, namely that for flow capacity analysis, only single passage cases are required, and for efficiency analysis, only double passage cases are required. Based on this discovery, in most cases there is no need to perform CFD simulations beyond two passages when analyzing manufacturing variation (additional components would be required to verify this finding is applicable on most airfoils). This provides a very powerful methodology and valuable insights for the effects of manufacturing variation on turbine row performance.

4.2.2 Predicting Feature Based Variation in Aerodynamic Performance

Once the aerodynamic analysis was performed on all 100 blades, the geometric and analytical results were used to perform probabilistic analysis both single and double passage data. Single passage analysis assumed all blades in the annulus were the same, and the double passage analysis utilized two randomly selected blades that were replicated through the annulus. This kind of analysis is a cascade model which is used to take advantage of periodicity and to reduce computational expense. This is visually represented by Figure 6.

Data on the aerodynamic performance of the blades were used to create a surrogate model. The data used were the geometric measures of the blade and the resulting corrected flow and efficiency. Fourteen geometric properties were measured at 18 cross sections along the length of the blade. In order to streamline the analysis, the geometry of the blades was simplified by using the average measurement across the length of the blade and only 13 of the 14 parameters were used for the surrogate model because of very high correlation between two of the parameters. The variables describing the average geometry of each blade are shown in Table 2.

Table 2. Geometric input variables in the aerodynamic surrogate model.

Geometric properties
Angle_Leading_Edge
Angle_Trailing_Edge
Axial_Position
Camber_Tmax
Chord_Length
Max_Camber
Max_Thickness
Position_Trailing_Edge
Position_Max_Thickness
Radius_Leading_Edge
Stagger_Angle
Tangential_Position
Thickness_Trailing_Edge

A design of experiments was performed to obtain additional information outside the observed variability in the geometric properties. The experiments were determined by selecting the model inputs to which the corrected flow and efficiency are the most sensitive. Both the corrected flow and efficiency were found to be the most sensitive to the tangential position. Since the tangential position was found to be the most important variable, variation in tangential position along the length of the blade was incorporated into the design. In order to capture this variation, the tangential position was calculated in 4 regions along the length of the blade. These regional values were calculated as the average of slice 1-4, slice 5-8, slice 9-13, and slice 14-18. In order to reduce the number of experiments, removal of inputs was performed in a stepwise fashion beginning with the input with the lowest sensitivity, with a new response surface generated after each removal. The cross validation R^2 (CV R^2) value of the new response surface was compared to the original surface, and variables were removed as long as the CV R^2 was within 1% of the original value. The CV R^2 was based on leave-one-out cross-validation residuals. Using the remaining variables, a Latin hypercube sampling algorithm was used to generate a design of experiments where the range of each variable was set to the mean ±3 standard deviations (SD). In addition, a correlation matrix was calculated and incorporated into the Latin hypercube sampling algorithm so that the sampled variables maintained the same correlations. The number of Latin hypercube samples was determined by following the rule of thumb that the samples should be ~10 times the number of variables.

A Gaussian process response surface using the 13 average geometric properties provided the best fit for both the corrected flow and efficiency compared to a polynomial regression model. A 2D visualization of the response surface is shown in Figure 9 and Figure 10. For the response surface, the x-axis utilized scaled coordinates, where the scaling was a linear transformation that mapped the minimum value from the data to a scaled coordinate of -1 and the maximum value to a scaled coordinate of 1. The representation shows how one variable affects the response in an average sense with respect to the other variables. The CV R^2 of the response surface was 0.9899 for corrected flow and 0.9208 for efficiency.

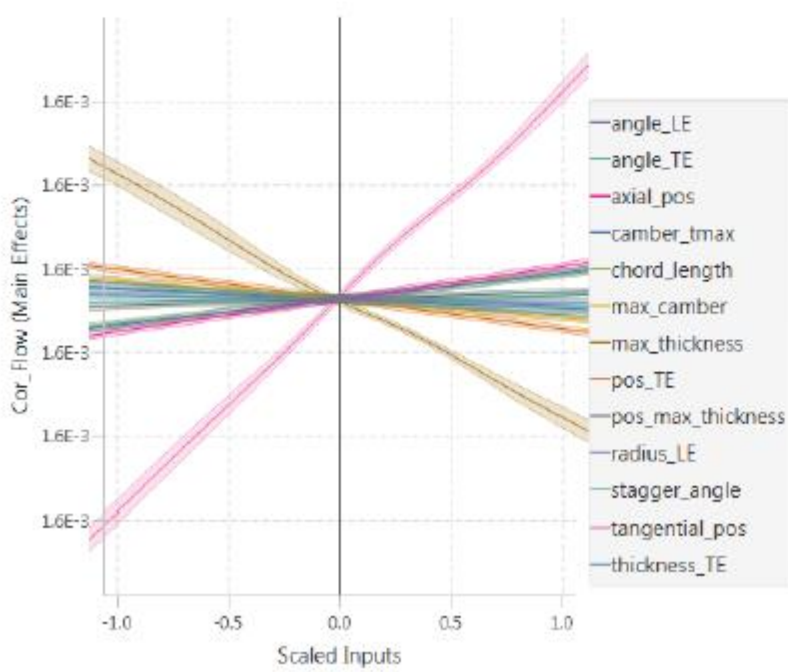


Figure 9. 2D representation of the surrogate model for corrected flow
(The shaded regions indicate the 95% confidence intervals for the model predictions)

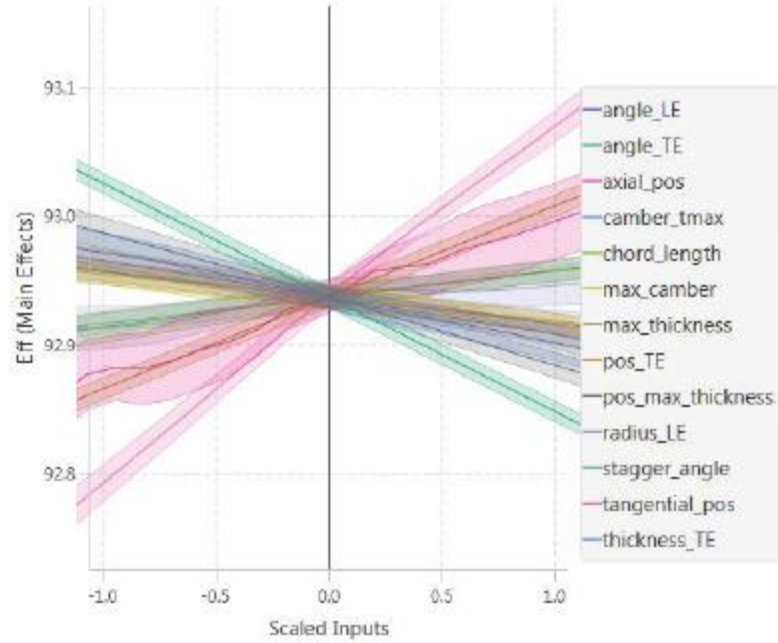


Figure 10. 2D representation of the surrogate model for efficiency
(The shaded regions indicate the 95% confidence intervals for the model predictions)

The sensitivity analyses for each surrogate model are shown in Figure 11 and Figure 12.

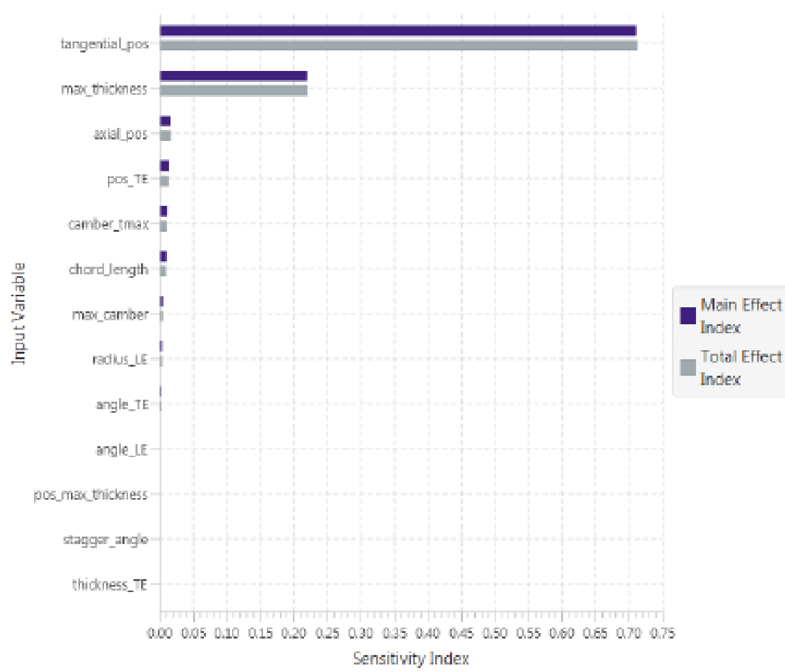


Figure 11. Sensitivity analysis for corrected flow surrogate model 5

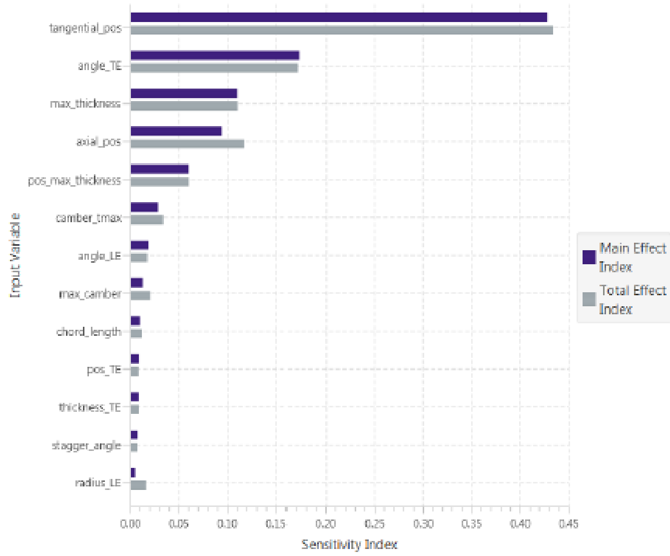


Figure 12. Sensitivity analysis for the efficiency surrogate model

For efficiency, removing variables reduced the CV R^2 by more than 1%, so all variables were retained for the surrogate model. The sensitivity analysis for corrected flow demonstrated very low sensitivity to several geometric variables. The input reduction technique used in the design of experiments analysis was utilized to create a surrogate model with the least number of variables required to maintain a high CV R^2 value. This resulted in a surrogate model for corrected flow that utilized the tangential position, maximum thickness, axial position, trailing edge position, camber tmax, chord length, and maximum camber. The resulting surrogate model had a CV R^2 of 0.9871 (difference of 0.3% against the original CV R^2) and is visualized in Figure 13.

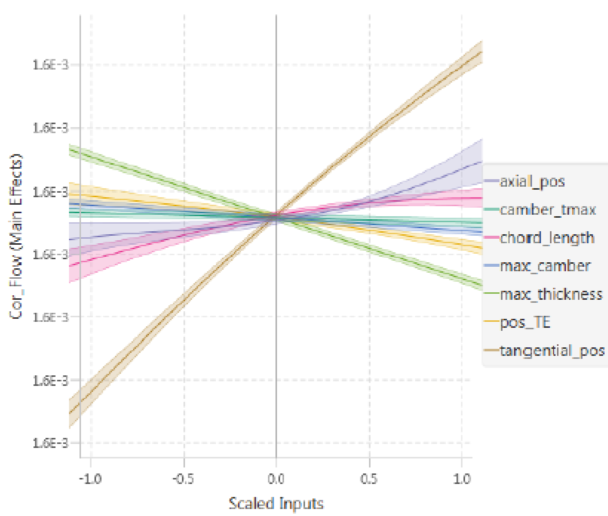


Figure 13. Surrogate model for corrected flow with reduced input set

For the design of experiments, a total of 14 variables were sampled (Table 3), since the trailing edge position and thickness variables were removed. A total of 150 Latin hypercube samples were generated within the sampled range given in Table 3.

Table 3. Variables used for the DoE.

Geometric property	Mean -3 SD	Mean +3 SD
Angle_Leading_Edge	47.8621	51.5368
Angle_Trailing_Edge	19.2363	21.0476
Axial_Position	-0.01026	-0.00988
Camber_Tmax	0.002737	0.002896
Chord_Length	0.023412	0.023904
Max_Camber	0.000248	0.000308
Max_Thickness	0.003587	0.00374
Position_Max_Thickness	0.334518	0.343787
Radius_Leading_Edge	0.137715	0.146094
Stagger_Angle	0.000451	0.000599
Tangential_Position_L1	56.3061	56.913
Tangential_Position_L2	52.7145	53.7343
Tangential_Position_L3	46.76	48.6527
Tangential_Position_L4	37.7558	40.4458

By creating a surrogate model for the aerodynamic performance of the component, exploring a large portion of the design space quickly allows for easy access to performance predictions. This can be used to understand the performance impact of using various manufacturing tolerances and how the performance of the part relates to the cost. The application of this surrogate model is further discussed in Section 4.5.

Surrogate modeling and variation analysis was performed on the double passage data as well, but correlation of the model was deemed poor and therefore single passage was the primary focus during the cost vs. performance analysis described in later sections. Further details on the double passage analysis are described in the Section 10.2 of this report.

4.3 Predicting As-Manufactured Structural Performance and Variation

There were two primary focuses with this task. First, was to develop an automated process of taking the 3D solid generated by 3D Systems process (refer to 4.1) and running structural analysis on the component to predict the as-manufactured structural performance. Second, was to analyze the variation of structural performance based on a parameterized model and create a surrogate model to explore the design space for the cost vs. performance study. This work was primarily done by the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology.

4.3.1 Predicting As-Manufactured Structural Performance

The first task involved creating an automated process for the as-manufactured blade geometry models which performed the following:

- Generate named selections for the as-built blade geometry model
- Add a dummy parameter to each as-built geometry model
- Perform structural analysis using ANSYS for the as-built geometry models and generate structural performance results. Other structural analysis software should be capabile of performing the steps described in this section.

The overall system architecture of this process is shown in Figure 14.

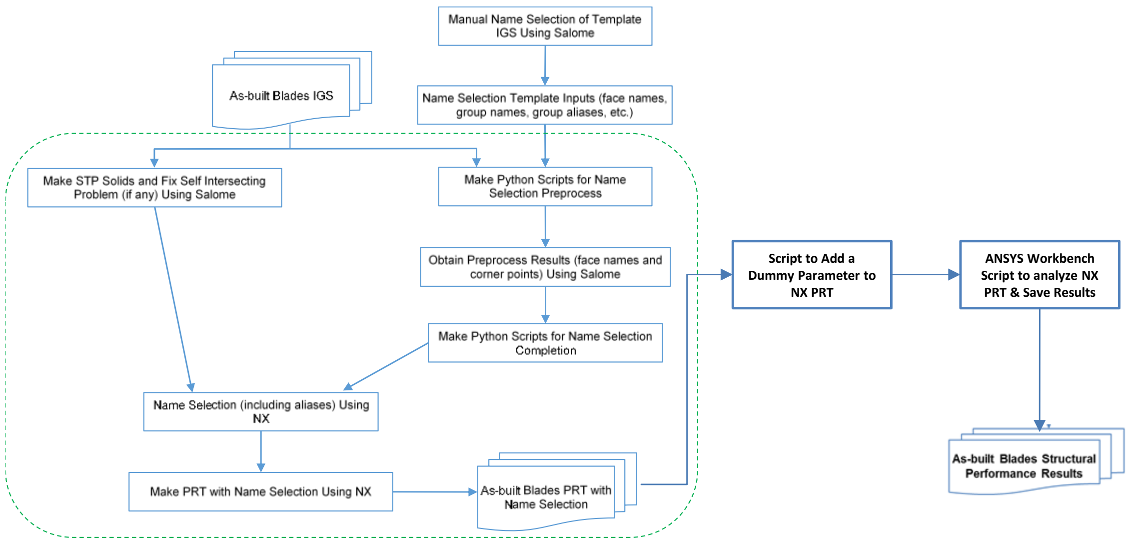


Figure 14. Structural performance system architecture

4.3.1.1 Generate named selections for the as-built blade geometry model

The named selections are predefined groups of geometry used in ANSYS pre and post processing. They are essential for automation of the structural analysis process in ANSYS. Developing an automated process to generate named selections required by ANSYS is the first step toward a fully automated process for as-built blades.

The final version of the automated process is summarized below in the flowchart shown in Figure 15.

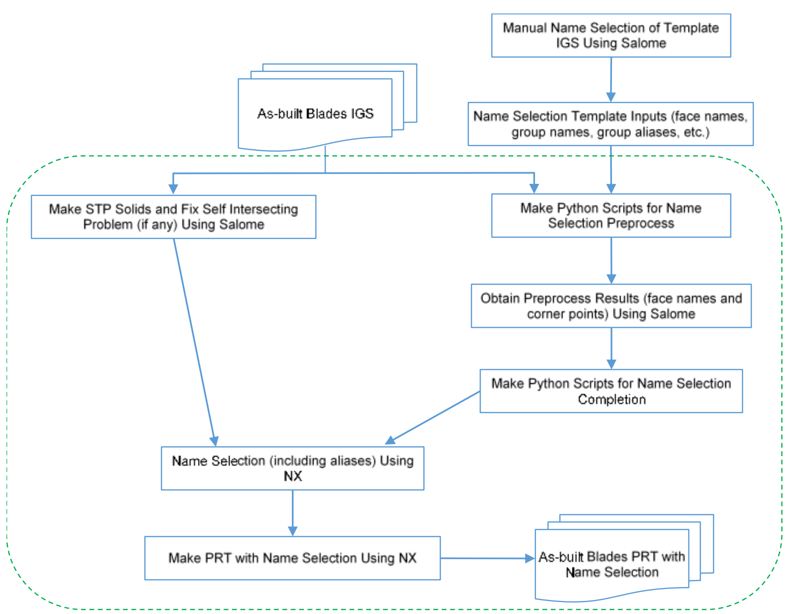


Figure 15. Flowchart of automated name selection

The automatic name selection is accomplished in two sub-steps. The first sub-step is the name selection pre-process and the second sub-step is the name selection completion in NX.

The first sub-step (name selection pre-processing) requires a template of the as-built geometry. The topology of the faces are similar between the template blade and all as-built blades generated by Geomagic. This means the shapes and locations of the faces, and total number of faces are similar between them, see Figure 16. By creating a template it makes automation possible.

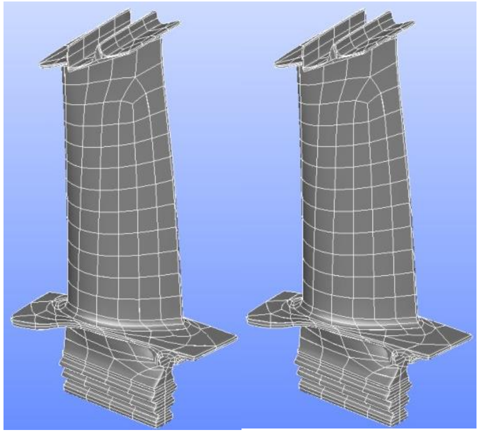


Figure 16. Similar topology of template blade (L) and as-built blade (R)

Both the template and the as-built blades have a total of 861 faces. The template was created with a name selection for each of the faces (using Salome Platform 7.8.0 – free open source CAD package) and Python scripts calling functions in Salome are used to map the faces of an as-built blade to the template blade. This mapping is done by the following method:

1. The selection of candidate face(s) is done by using the centroid of a face for selection of possible mapping face(s). This is done by finding the centroid of the as-built and the template blade and calculating the distance between them and determining if the as-built matches the template within a certain threshold and selects them as a candidate.

2. Final selection of the mapping blade face for a template face is made by cross-match test by finding the minimum distance blade face in the set of candidates and pair the as-built and template together.

3. Collect all the not-paired as-built blade faces and template faces, and repeat the matching process above.

The mapped faces from an as-built blade are renamed to corresponding names in the template and the native order number, name and coordinates of corner points of each face are output into a text file.

Once the name selection preprocessing is finished, Python scripts calling functions of NX 10.0.3 pull in the output text file from Salome (which includes the order number, name information and coordinates of corner points of faces). The Python scripts maps the faces of an as-built blade based on the corner points and then outputs a PRT file with name selection information for each as-built blade.

1. Preparation of data by reading in the names and corner points of each face then calculates the distance of each corner point of the face to a specific face of the as-built blade in NX.

2. If the distances of all corner points are within a tiny threshold, this specific face is selected and it is assigned the name.

The named selections generated through this automated process enables the automation of the structural analysis using ANSYS. Previously, this process required manual intervention which was time intensive. By automating this name selection with a template it provides a large efficiency improvement to current methods.

4.3.1.2 Add a dummy parameter to each as-built geometry model

Another required enabler to the automated structural analysis in ANSYS is to add a dummy parameter into each NX part file. The value of this dummy parameter will be changed by the ANSYS workbench script so ANSYS Design modeler will refresh its geometry to process the next geometry model.

A simple VB code was developed to allow NX to open the as-built geometry models, add a dummy parameter, and save the model.

4.3.1.3 Develop an automated ANSYS model to process as-built blades

The analysis flow of the ANSYS model to process as-built blades is shown in Figure 17.

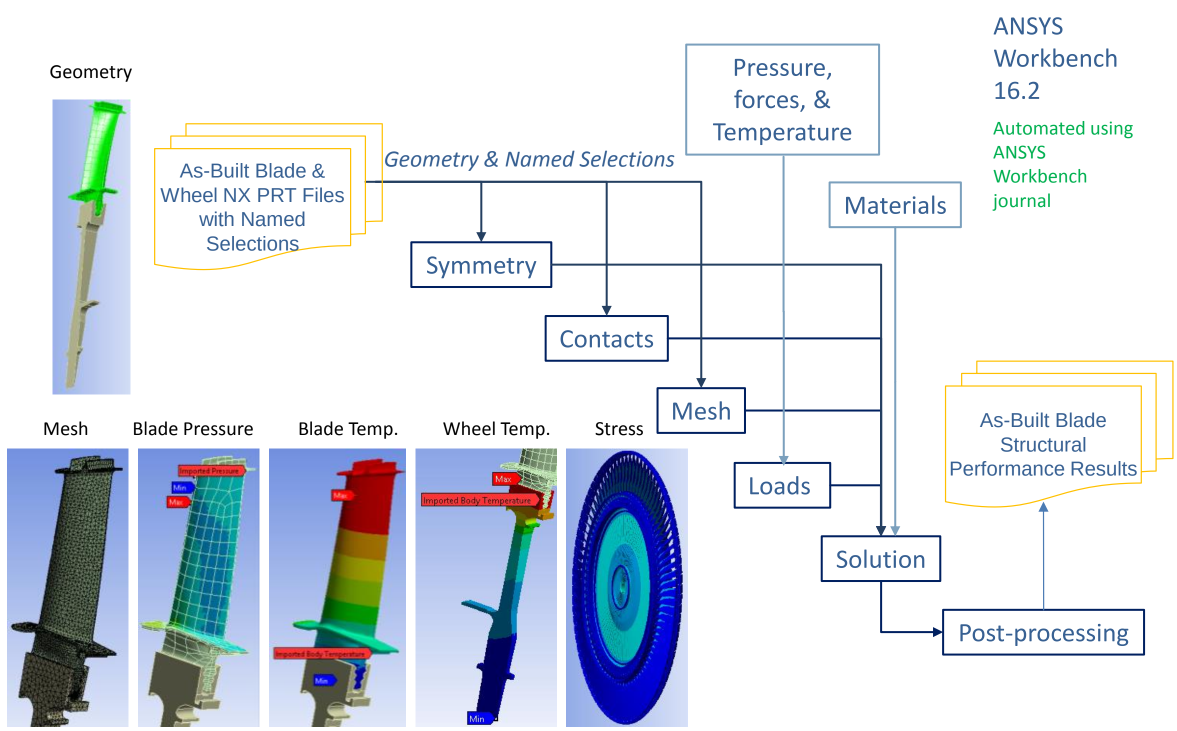


Figure 17. ANSYS analysis workflow

The as-built blade geometry along with its named selections was imported to the ANSYS model without pre-assembly. All the as-built blade geometry models were aligned with the as-designed model using the bottom teeth contact faces and the vertical blade axial face as datum faces. Considering the tight manufacturing tolerance on the contact surfaces and ANSYS's capability to handle interpenetration between the models, the blade geometry models were imported into the ANSYS models and test runs shows this approach was successful. The import of as-built blade geometry models erases all previous manual geometry selections. All the manual geometry selections were replaced by named selections for the purpose of automation.

Automation of the ANSYS model is straightforward, except the import of the as-built blade geometry into the ANSYS model. The method developed was a set of scripts to import the as-built blade geometry into ANSYS using renaming approach. After telling the scripts which as-built blades are to be processed and where they are located, all the following steps in the process were automated:

1. Create a dummy parameter in each as-built blade geometry file
2. Rename an as-built blade geometry to be processed to the one currently in the ANSYS model
3. Use the dummy parameter to force ANSYS to import the as-built blade
4. Refresh the model and run the analysis
5. Extract and save results
6. Rename the as-built geometry file name back and rename the result files
7. Repeat steps 2 to 6 for the next as-built blade geometry till all the as-built blades are processed

4.3.2 Predicting Variations in Structural Performance

ASDL and Rolls-Royce jointly developed an automated process to parametrically varying manufacturing deviations of key features in the as-designed blade model and analyze the parameterized models. The automated process was used to run a Design of Experiments (DoE) to sample the design space. The results were used to construct surrogate models for sensitivity analysis and probabilistic analysis.

This process included following steps:

- Develop an automated modeling and simulation process for the DoE
- Running the DoE
- Analyzing the results to create a surrogate model

The overall system architecture is shown in Figure 18.

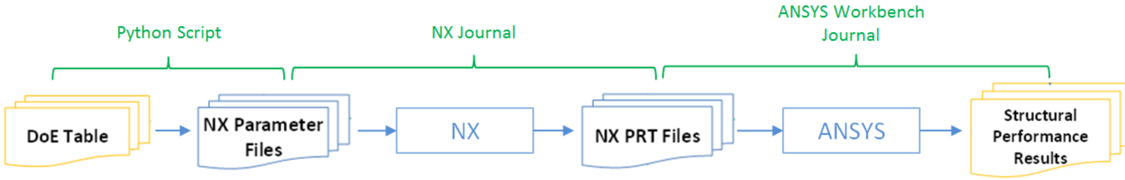


Figure 18. Structural performance variation system architecture

4.3.2.1 Develop an automated modeling and simulation process for the DoE

Rolls-Royce developed a standard parametric CAD model in NX that parameterized certain key features of the turbine blade, including: shroud, stalk, platform, and the airfoil. In addition to supplying a parametric model, Rolls-Royce provided ranges for these parameters based on as-designed tolerances in the drawing. ASDL generated a fractional design DoE as the initial test for the automation.

In order to automate the analysis of the turbine blade via a DoE, ASDL developed scripts to read from a DoE table to generate NX part files that were then passed those files into ANSYS to process the part for results. As shown in Figure 18, the following scripts were developed to automate this process.

- A Python script that reads in the DoE table and generates NX parameter expression files accordingly. The Python script first reads in the DOE file and the parameter expression file. It then loops through each row in the DOE file and looks for the parameter name given in the DOE file in the parameter expression file. When it finds it, it changes the value for that specific DOE run. It saves each parameter set or DOE run in a different parameter expression file labeled sequentially.

- A NX journal that reads in the NX parameter expression files and generates NX part files accordingly. The NX journal file loops through the new parameter expression files. For each file, it updates the parameters in the NX model. It then saves a new part file for each DOE run. These new part files can then be analyzed automatically using the analysis automation process. Further information can be found in the User's Guide document (Appendix E).

- An ANSYS workbench journal reads in the NX part files, processes these files, and generates results. The ANSYS workbench journal that was previously described in Section 4.3.1 was updated with a few minor changes for the DoE parametric model runs.

- A batch command is used to combine results of all the cases, then a VBA script is used to reformat the combined results so they are ready for further analysis

4.3.2.2 Running the DoE

Sixteen independent parameters were selected for the surrogate modeling. These parameters and there ranges are listed in Table 4.

Table 4. Parameters used in surrogate modeling

Parameters		Tolerance	110% Tolerance
DS_AF_TAN	Airfoil tilt tangential	±0.005 inch	±0.0055 inch
DS_AF_X	Airfoil tilt along x axis	±0.005 inch	±0.0055 inch
DS_ATTACH_CP	Platform width (pressure side)	±0.003 inch	±0.0033 inch
DS_ATTACH_CR	Platform width (suction side)	±0.003 inch	±0.0033 inch
DS_PLATFORM_HEIGHT	Platform height	±0.0025 inch	±0.00275 inch
DS_PLATFORM_THK	Platform thickness	±0.005 inch	±0.0055 inch
DS_SHROUD_BS	Shroud width (pressure side)	±0.003 inch	±0.0033 inch
DS_SHROUD_BV	Shroud width (suction side)	±0.003 inch	±0.0033 inch
DS_STALK_PS_LE	Stalk leading edge thickness (pressure side)	±0.005 inch	±0.0055 inch
DS_STALK_PS_TE	Stalk trailing edge thickness (pressure side)	±0.005 inch	±0.0055 inch
DS_STALK_SS_LE_AJ	Stalk leading edge thickness (suction side, top)	±0.005 inch	±0.0055 inch
DS_STALK_SS_TE	Stalk trailing edge thickness (suction side)	±0.005 inch	±0.0055 inch
DS_AF_COMMON_QT	Airfoil leading edge thickness	±0.005 inch	±0.0055 inch
DS_AF_COMMON_WT	Airfoil twist angle (top of airfoil)	±0.5 degree	±0.55 degree
DS_SHROUD_THK	Shroud thickness	±0.005 inch	±0.0055 inch
DS_STALK_SS_LE_AM	Stalk leading edge thickness (suction side, bottom)	±0.005 inch	±0.0055 inch

Tolerances of 110% were used to set the ranges of the parameters. By analyzing to a tolerance past the print limits we are able to explore more of the design space and compare with the cost analysis for a large view of the cost vs. performance analysis. 110% was chosen because based on initial tests, it was determined this was the limit of the parametric model (any further tolerances caused issues for convergence).

4.3.2.3 Analyzing the results to create a surrogate model

Twenty responses including sectional max stresses, Margin of Safety (MS) for creep, Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) were tracked in the DoE cases and fitted in the surrogate modeling process.

Neural Nets was used to generate the surrogate model. During the Neural Net modeling process, 90% of the cases were randomly picked as the training cases used to generate the surrogates and the rest, 10%, were used to validate the generated surrogates. The summary of the R^2 values for the surrogates is listed in Table 5 as a reference of how well the surrogates fit the training and validation data.

Table 5. Summary of structural performance surrogate model fit

Responses	Training Fit	Validation Fit
Max Shroud Stress	0.94	0.93
MS Strength Shroud - Integrate	0.95	0.93
MS Strength Shroud - Burst	0.95	0.93
Max Platform Stress	0.96	0.94
MS Strength Platform - Integrate	0.96	0.94
MS Strength Platform - Burst	0.96	0.94
Max Stalk Stress	0.99	0.98
MS Strength Stalk - Integrate	0.99	0.98
MS Strength Stalk - Burst	0.99	0.98
MS Creep Airfoil	0.98	0.98
MS Creep Platform	0.98	0.98
MS LCF Platform	0.95	0.96
MS LCF Stalk	0.98	0.99
MS HCF Airfoil Hub	0.96	0.95
MS HCFStalk Top	0.99	0.98

A sectional view of the relationship between the responses and blade parameters is shown in Figure 19.

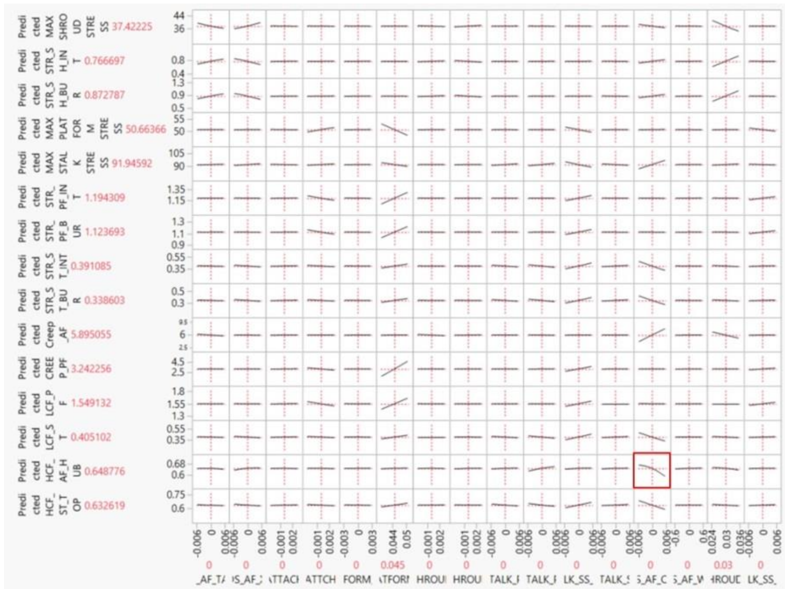


Figure 19. Response-parameter curves for structural performance

While the ranges of the parameters represent the manufacturing tolerances, which are very small, most of the relationships, except a few between the responses and parameters are close to linear. The most significant curvature shown (in the red box) is between the MS HCF airfoil hub and airfoil leading edge thickness. The MS HCF airfoil hub is calculated from max stress in airfoil hub, which is mostly influenced by the mass of the airfoil and the centrifugal force caused by rotation is the main contributor to the stress in the airfoil hub. In the parametric model used for this study, the changes in the mass of airfoil (volume) is modeled as a quadratic function of the changes in the airfoil leading edge thickness and leads to significant curvature.

The sensitivity plots between the responses and parameters generated during the surrogate modeling were also reviewed by and delivered to Rolls-Royce. The plots are bar charts with percentiles of responses' variability contributed by each parameter. An example sensitivity plot for max shroud stress is shown in the Figure 20. In this example, near 40% of variability in max shroud stress is contributed by shroud thickness (DS_SHROUD_THK).

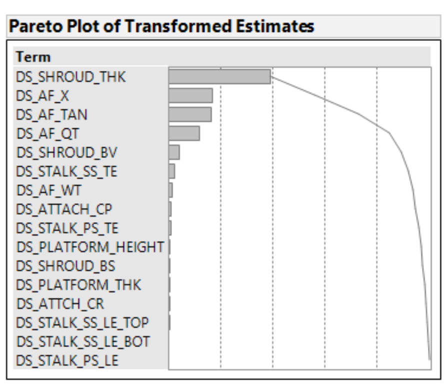


Figure 20. Sensitivity plot for max shroud stress

The surrogates are equations representing the responses from the physics-based simulations. Once validated, they provide a rapid way to run probabilistic analysis using Monte Carlo Simulation.

The input distributions for the probabilistic analysis could be obtained through linking the parameters to the manufacturing deviations in the scanned as-built blades. Unfortunately, these distributions are not currently available. Therefore, symmetric triangular distributions were used as place holders in this study and can be replaced quickly once the realistic distributions are defined. Five thousand cases of Monte Carlo simulation were run for probabilistic analysis and the statistical results were reviewed by and submitted to Rolls-Royce.

Example statistical results are shown in the Figure 21.

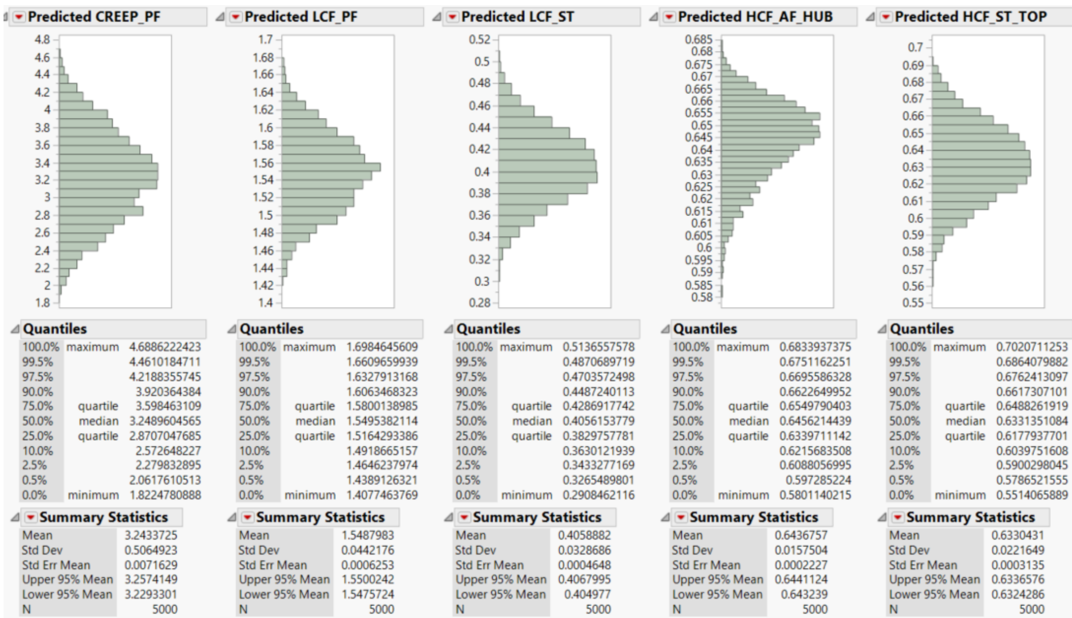


Figure 21. Example statistical results

The results include the plots of the distributions, quantiles, and statistics such as mean and standard deviations. By creating a surrogate model of the structural performance of the component, exploring a large portion of the design space quickly allows for easy access to performance predictions. This can be used to understand the performance impact of using various manufacturing tolerances and how the performance of the part relates to the cost. The application of this surrogate model is further discussed in Section 4.5.

4.4 Manufacturing Cost Analysis

The focus of this task was to develop a method to determine a feature-based should-cost given a wide range of manufacturing tolerances. Tools and methods developed in the DARPA Adaptive Vehicle Make (AVM) Program by the Penn State Applied Research Lab were used as the basis of the manufacturing cost analysis and the AVM Tools were extended to provide automated feature-based cost applications. From this analysis a surrogate model can be created to explore and compare the design space of both cost and performance. This work was primarily done by Penn State Applied Research Lab (Penn State ARL).

4.4.1 Predicting "Should-Be" Feature Based Cost

4.4.1.1 Manufacturing Cost Approach

aPriori is a commercially available product cost management software tool that uses a Virtual Production Environment (VPE) to estimate the cost of creating the 'features' of a particular design. A VPE is a library of manufacturing models that represent manufacturing capabilities, including processes/operations and specific equipment, materials, labor and overhead costs. The VPE also contains the underlying cost models, which map geometric features to appropriate manufacturing processes and equipment in order to predict the cost of a part.

The majority of aPriori users interact with the tool through the standard graphical user interface and are thus able to provide additional information about the part such as feature tolerances. However, in this project, the costing engine was employed in the software as a service (SaaS) type implementation, where the required information needed to be passed to the software for analysis. In addition, the 'features' that are identified by aPriori did not match exactly with the design parameters used to model and analyze performance. Therefore, a mapping from design parameters to manufacturing features was developed and employed to enable direct comparison between cost and performance.

The tools developed in AVM (including the SaaS implementation of aPriori) were extended to include the mapping function and automated, feature-based costing. The workflow in Figure 22 was developed to identify the manufacturing features, map those features to the design parameters, prescribe tolerance values for those features, invoke the costing engine, process the results, and pass them to the comparison tools.

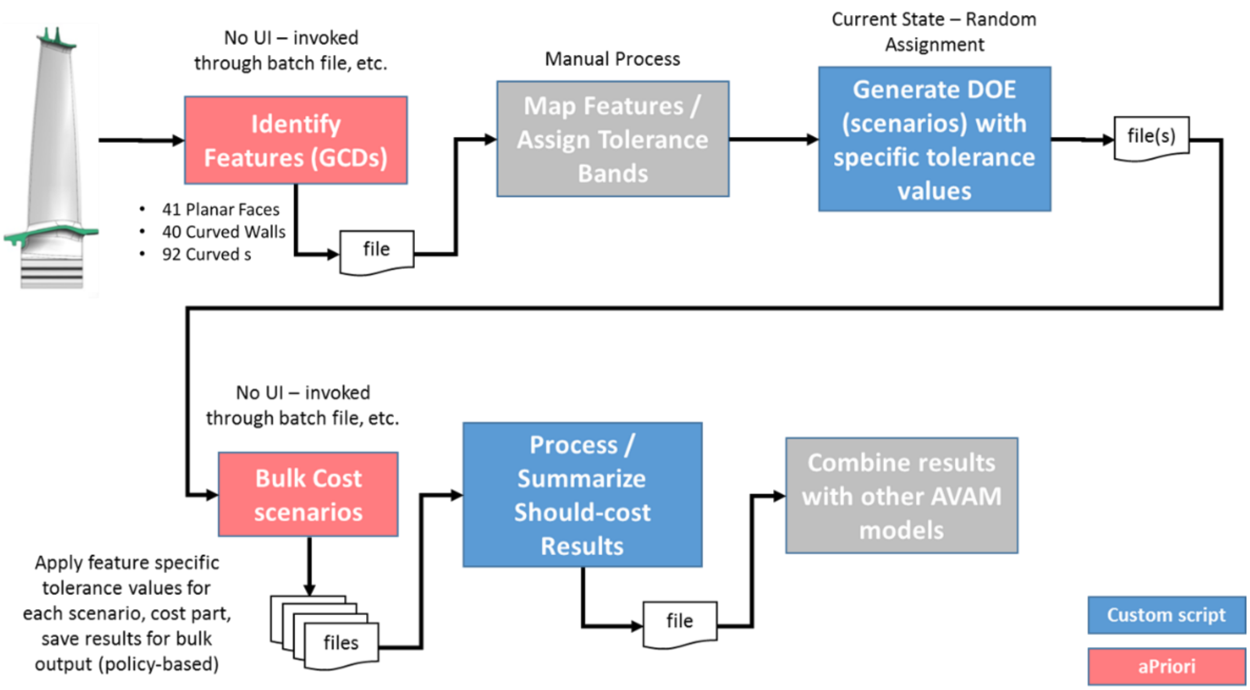


Figure 22. Manufacturing cost analysis system architecture

The tools/scripts developed in this project are two-fold and both integrated into the DOME framework for inclusion in the DMC. The two red boxes in Figure 22 indicate where aPriori was integrated into the system. The top box represents the use of aPriori Enterprise software to identify the GCDs and code was developed in this project to extract the GCD information from the aPriori output and populate the input for the Map Features / Assign Tolerance Bands box. The bottom box represents the Costing of the individual scenarios, i.e. specific tolerance settings for feature groups. A macro was developed by aPriori to accept the input file that defines each scenario and invokes the costing engine. A new interface was developed by ARL Penn State to execute the aPriori developed macro.

The primary tool included aPriori as described in Figure 22. Scripts were developed by aPriori to accept the tolerance value inputs (see bottom red box in Figure 22). The costing portion of the workflow was integrated into a SaaS architecture with a Rails front-end wrapped in a DOME model to send the input to the software hosted at PSU to perform costing analyses. The aPriori scripts can be used by developers to interact with an existing installation of aPriori. Should someone wish to implement this tool at their facility, they would need to have a license of aPriori and set up the required interfaces provided in the source code.

The secondary tool used the aPriori implementation to create a very large dataset that was used to construct a surrogate model. The surrogate model was wrapped in a DOME model and deployed on the NCSA servers and integrated with the other analyses to perform the combined analyses.

4.4.1.2 Manufacturing Cost Process

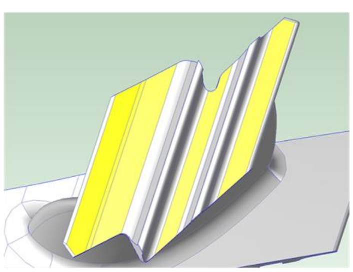
aPriori uses geometric reasoning to identify features of a part that impact cost. These geometric cost drivers (GCDs) link to the underlying manufacturing models in the virtual production environment (VPE), where appropriate manufacturing processes and equipment are selected to produce the component and predict its cost. The GCDs do not map directly to manufacturing features or design parameters, therefore the workflow includes a step to map the features to the GCDs and assign tolerance values. Table 6 shows the mapping for the demonstration part.

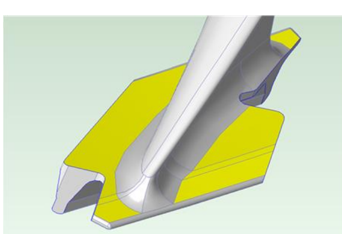
Table 6. Mapping table for design parameters to geometric cost drivers

	Structural Parameter	Cost Model Features
1	Shroud width (pressure side)	PlanarFace:40, PlanarFace:20, PlanarFace:25, PlanarFace:41, CurvedWall:21, CurvedWall:22, CurvedWall:25
2	Shroud width (suction side)	PlanarFace:39, PlanarFace:38, PlanarFace:37, CurvedWall:19, CurvedWall:40
3	Shroud thickness	CurvedWall:23, CurvedSurface:7, CurvedSurface:8, CurvedSurface:12, CurvedSurface:42, CurvedWall:20, CurvedWall:24, CurvedSurface:6, CurvedSurface:9, CurvedSurface:10, CurvedSurface:36, CurvedSurface:43
5	Platform width (pressure side)	PlanarFace:36
4	Platform width (suction side)	PlanarFace:35
6	Platform thickness	CurvedWall:18, CurvedSurface:2, CurvedSurface:5, CurvedSurface:26, CurvedSurface:28, CurvedSurface:31, CurvedSurface:32, CurvedWall:13, CurvedWall:26, CurvedSurface:3, CurvedSurface:4, CurvedSurface:25, CurvedSurface:27, CurvedSurface:29, CurvedSurface:30
7	Platform height	CurvedWall:18, CurvedSurface:2, CurvedSurface:5, CurvedSurface:26, CurvedSurface:28, CurvedSurface:31, CurvedSurface:32, PlanarFace:1
8	Stalk leading edge thickness (pressure side)	PlanarFace:12, CurvedSurface:23, CurvedSurface:57
9	Stalk trailing edge thickness (pressure side)	
10	Stalk leading edge thickness suction side, top)	PlanarFace:14, CurvedSurface:55, CurvedSurface:58
11	Stalk trailing edge thickness suction side)	
12	Stalk leading edge thickness suction side, bottom)	
13	Airfoil tilt tangential	CurvedSurface:79, CurvedSurface:80, CurvedSurface:81
14	Airfoil tilt along x axis	
15	Airfoil leading edge thickness	
16	Airfoil twist angle (top of airfoil)	N/A

Notice that for each design parameter there is one or more geometric cost drivers that are used characterize the manufacturing cost. In addition, the same GCD can be used in the characterization of multiple design parameters. Figure 23 shows the detailed mapping of the GCDs to the design shroud thickness parameter.

Parameters		Tolerance	110% Tolerance
DS_SHROUD_BS	Shroud width (pressure side)	±0.003 inch	±0.0033 inch
DS_SHROUD_BV	Shroud width (suction side)	±0.003 inch	±0.0033 inch
DS_SHROUD_THK	Shroud thickness	±0.005 inch	±0.0055 inch





Cost-model Identified Features:

CurvedWall:23

CurvedSurface:7
CurvedSurface:8
CurvedSurface:12
CurvedSurface:42

CurvedWall:20
CurvedWall:24

CurvedSurface:6
CurvedSurface:9
CurvedSurface:10
CurvedSurface:36
CurvedSurface:43

1 parameter ~ 12 surface features

Each feature assumes same tolerance policy

Figure 23. Detailed mapping with tolerance band for one parameter

Figure 23 also shows the nominal tolerance and the expanded tolerance for the design parameters. Each GCD has multiple tolerance types that can be set. For example, the Planar Face GCD has profile, roughness, flatness, parallelism, and perpendicularity tolerances. Table 7 shows the various tolerance types for the GCDs.

To develop a manufacturing cost profile for each GCD, the project team developed 6 levels to evaluate the cost using the aPriori cost engine. Initially 8 levels were analyzed, but after initial tests it was determined that only 6 of the 8 had an effect. The 6 levels include:

- loose10 (110% of nominal)
- nominal (± 0.005” tolerance)
- tight10 (90% of nominal)
- tight25 (75% of nominal)
- tight50 (50% of nominal)
- tight90 (10% of nominal)

The second column in Table 7 shows the tolerance levels and corresponding tolerance values for the GCD types.

Table 7. Geometric cost driver, tolerance policy, and tolerance setting (values are shown as total range in millimeters - example: .254 mm = ±0.005”)

Type	Tol Policy	profile	roughness (um)	flatness	parallel	perpendicular	diamTol	positionTol	concentricity	cylindricity	runout	circularity	straight
planarFace	loose10	0.2794	2.64	0.2794	0.2794	0.2794							
planarFace	nominal	0.254	2.4	0.254	0.254	0.254							
planarFace	tight10	0.2286	2.16	0.2286	0.2286	0.2286							
planarFace	tight25	0.1905	1.8	0.1905	0.1905	0.1905							
planarFace	tight50	0.127	1.2	0.127	0.127	0.127							
planarFace	tight90	0.0254	0.24	0.0254	0.0254	0.0254							
curvedWall	loose10	0.2794	2.64			0.2794	0.2794	0.2794	0.2794	0.2794	0.2794	0.2794	0.2794
curvedWall	nominal	0.254	2.4			0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254
curvedWall	tight10	0.2286	2.16			0.2286	0.2286	0.2286	0.2286	0.2286	0.2286	0.2286	0.2286
curvedWall	tight25	0.1905	1.8			0.1905	0.1905	0.1905	0.1905	0.1905	0.1905	0.1905	0.1905
curvedWall	tight50	0.127	1.2			0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127
curvedWall	tight90	0.0254	0.24			0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
curvedSurface	loose10	0.2794	2.64								0.2794		
curvedSurface	nominal	0.254	2.4								0.254		
curvedSurface	tight10	0.2286	2.16								0.2286		
curvedSurface	tight25	0.1905	1.8								0.1905		
curvedSurface	tight50	0.127	1.2								0.127		
curvedSurface	tight90	0.0254	0.24								0.0254		

Tolerance policies were applied to each of the features by performance parameter which results in a particular tolerance scenario. Each scenario was evaluated by the costing engine to determine the manufacturing cost. Table 8 shows a sample of the scenario settings and resulting costs.

Table 8. Scenario settings and cost estimates - sample

Shroud width (pressure side)	Shroud width (suction side)	Shroud thickness	Platform width (pressure side)	Platform width (suction side)	Platform thickness	Platform height	Stalk leading edge thickness (pressure side)	Stalk trailing edge thickness (pressure side)	Stalk leading edge thickness suction side (top)	Stalk trailing edge thickness (suction side)	Stalk leading edge thickness suction side (bottom)	Airfoil tilt tangential	Airfoil tilt along x axis	Airfoil leading edge thickness	cost
loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	loose10	29.86
nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	nominal	52.33
tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	tight90	326.34
nominal	nominal	nominal	tight10	tight25	nominal	tight10	tight90	tight90	nominal	tight50	nominal	loose10	tight50	loose10	122.63
tight50	tight10	tight25	tight10	loose10	nominal	tight25	loose10	tight50	loose10	tight10	tight90	tight90	tight90	tight25	239.92
tight50	loose10	loose10	loose10	loose10	nominal	tight25	tight50	loose10	tight25	loose10	loose10	nominal	nominal	loose10	58.23
nominal	tight10	loose10	tight25	tight50	tight25	tight25	nominal	tight90	tight25	tight90	tight50	tight50	tight50	tight50	138.53
loose10	tight10	tight10	tight25	loose10	tight25	tight90	tight50	loose10	tight10	tight25	tight10	tight50	tight50	nominal	111.38
nominal	tight90	nominal	tight10	tight25	tight10	tight90	loose10	tight25	tight25	tight50	tight25	tight25	tight90	tight10	247.26
nominal	tight50	loose10	tight50	tight25	tight50	tight50	loose10	tight10	tight10	tight25	nominal	tight25	tight50	tight50	98.92
tight50	tight25	tight10	tight50	tight10	tight10	tight25	loose10	tight50	tight25	tight25	nominal	loose10	loose10	loose10	35.77
loose10	loose10	loose10	tight50	loose10	tight10	tight10	tight10	loose10	tight10	tight50	loose10	loose10	nominal	loose10	55.09
tight10	tight25	tight50	tight90	tight90	tight90	loose10	tight25	tight25	loose10	tight50	loose10	tight90	tight10	nominal	241.64
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

The first three scenarios (rows of data) show boundary settings where the tolerance settings for all parameters were set to loose10, nominal, and tight90. The preliminary results showed the expected outcome in that the loose tolerance settings were less expensive (easier to achieve) than the nominal and tight tolerance values.

4.4.1.3 Data Analysis

To validate the process, roughly 11,000 scenarios were randomly generated and analyzed for estimated cost. Figure 24 shows the preliminary set of data points, where the Red colored points indicate the boundary scenarios where each of the parameters were set to one of the 6 tolerance levels. It should be noted that it takes about 45 seconds/scenario to perform an analysis.

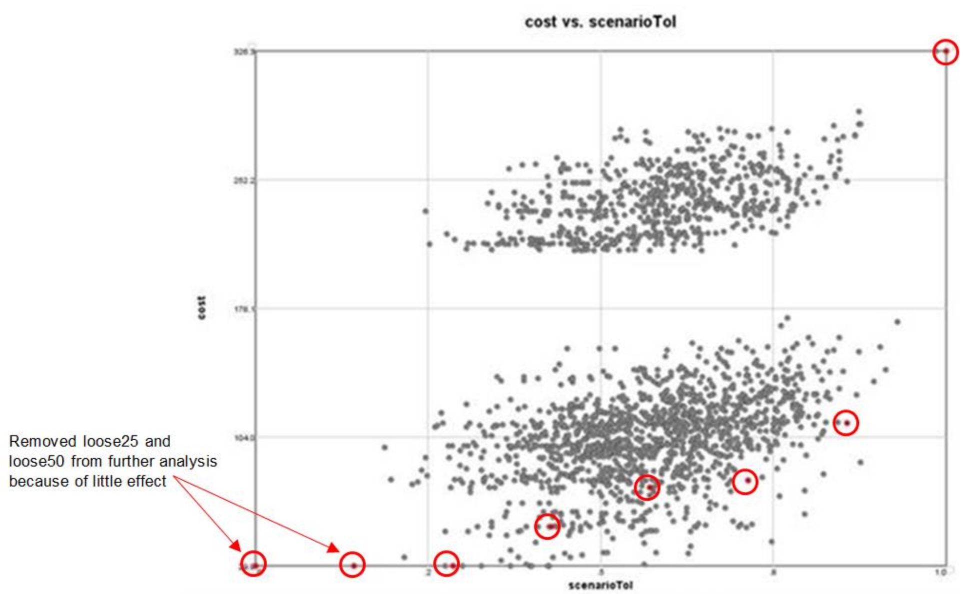


Figure 24. Preliminary data analysis results – cost vs. tolerance settings

These preliminary results show two interesting findings: 1) that the costing estimation process is behaving as expected and 2) there are two groupings in the results. The x-axis represents a composite value for the tolerances where the tolerances increase (tighten) from left to right. The y-axis represents estimated cost for the given scenario. The red points in the graph show that the cost is increasing as the tolerances tighten, as expected. The two groupings are a result of 3 design parameters dominating the cost due to their size. When any of these three parameters have a tight tolerance setting, the cost is high which results in the data spread shown in Figure 24.

A sensitivity analysis was performed to understand the two groups identified in the output data. Figure 25 shows the results of the sensitivity analysis indicating that the parameters corresponding with G13, G14, and G15 (Airfoil tilt tangential, Airfoil tilt along x axis, Airfoil leading edge thickness) are the most significant contributors to the variance in cost from the tolerance scenarios. These are the three largest surfaces on the demonstration component, and when the tolerances on those surfaces are tightened it intuitively increases the cost at a faster rate than other smaller features.

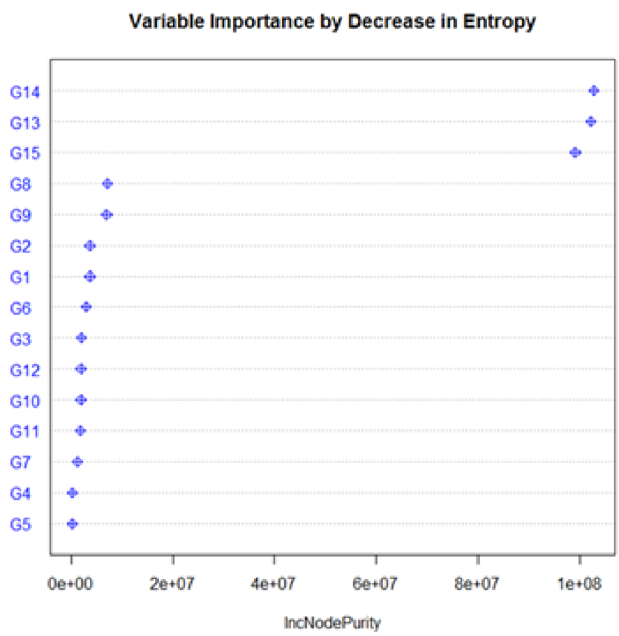


Figure 25. Sensitivity analysis results

4.4.2 Manufacturing Cost Surrogate Modeling

4.4.2.1 Creation of Costing Surrogate Model

Initially, the manufacturing cost for each scenario was to be evaluated and stored in a database for comparison with performance analyses. There were two main challenges in this approach: 1) the number of data points quickly increased to an intractable level, and 2) aPriori license agreement restricted the analyses to the servers at ARL Penn State. Because of these reasons it was decided to create a surrogate model for the manufacturing costs to enable a process to perform the comparison with the performance analyses.

A full-factorial experimental design was proposed that would enable users to perform cost vs performance trade-offs. For instance, using only one replication per point, the full factorial experiment would require 470,184,984,576 runs (6 tolerance settings for 15 design parameters). Since the runs take about 0.8 minutes each, fully exploring the search space would take approximately 715.65 millenia on a single core machine.

Instead, we relied on a machine learning technique known as random forests to develop a surrogate model that could essentially provide real-time cost results.

The random forest algorithm is based on decision trees, where a tree that best classifies an outcome is developed from a recursive algorithm. A basic example decision tree for determining cost is shown in Figure 26.

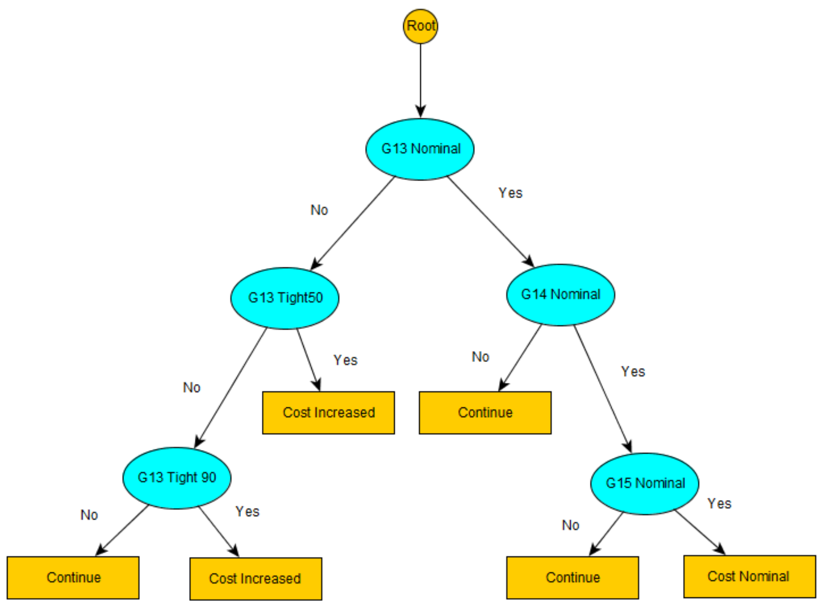


Figure 26. Example tree for costing data.

The algorithm picks the feature that best describes a split by minimizing entropy or using the GINI coefficient. The decision tree then attempts to minimize the depth of the tree needed to get accurate results via an additional pruning algorithm.

Decision trees and a random forest differ in that the random forest algorithm generates a multitude of decision trees and when a new input is to be computed, the input is passed into all of these trees [usually around 500-2000], which then estimate the output individually. Each approximation by a tree represents a "vote" for that value. The approximation receiving the most "votes" is the overall weighted average of the approximations, and is the output value of the forest.

Preliminary exploration shown in Figure 25 demonstrated that several variables were more important by up to seven orders of magnitude. This means that much of the search space could be approximated with minimal sampling. Once the initial model was validated, the team began to manipulate the more important variables to get a higher resolution space where it mattered. The importance of G13,G14, and G15 are easily understood from the geometry, as they are the largest surfaces on the part.

The Random Forest algorithm was implemented in the R Programming language utilizing the built in algorithm due to its wide acceptance of its proven performance. This algorithm results in the response surface being modeled by many piecewise linear approximations. These approximations are linear themselves, but there are billions of these linear functions modeling the search space. When certain features are less important, excellent results are obtained by linearizing the entire response surface and spending more computational power on the difficult subsets of it. Also since random forests can be represented directly as binary structures, evaluating the model is very fast.

In the Random Forest algorithm, the key parameter to determine is how many decision trees should be included for the best prediction accuracy. In this project, it was found that 20,000 trees provided the best and most stable results.

4.4.2.2 Evaluation of Costing Surrogate Model

The Random Forrest model is, at its core, a statistical model and must be validated against the cost values generated via the aPriori Cost model to ensure that it is a good fit. Two simple tests used for validation were Percent Error and plotting actual cost values vs. the predicted cost values. Figure 27 shows the percent errors when comparing the actual and predicted values. There are a few spikes in the results, but overall the average Percent error is quite low at 0.3295%.

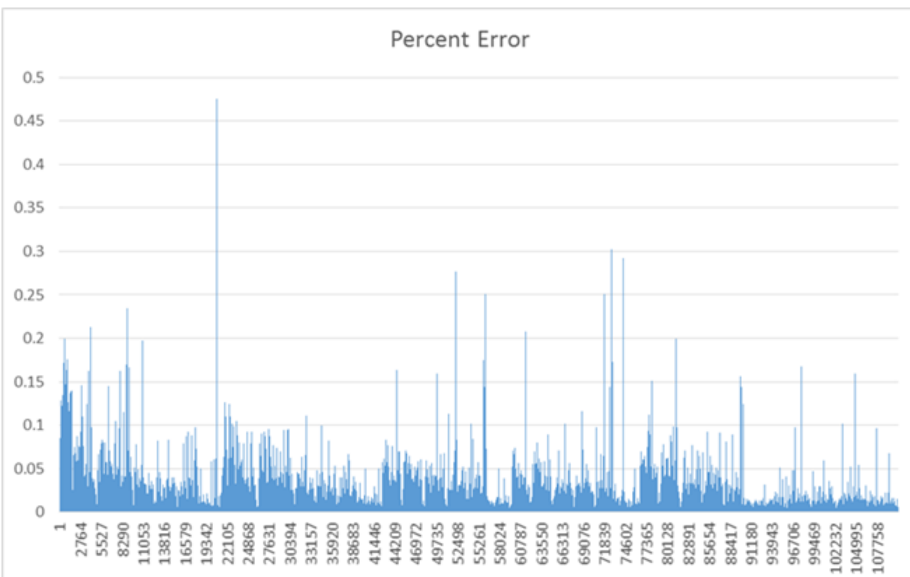


Figure 27. Absolute error test

When plotting the actual vs predicted cost values the red line should be at exactly 45 degrees for a model that fits the data perfectly (see Figure 28). In this case, the line is very close and bisects both of the data groupings through the midpoint. There are a few outliers in this chart, but it will improve with more data and a refitting of the model.

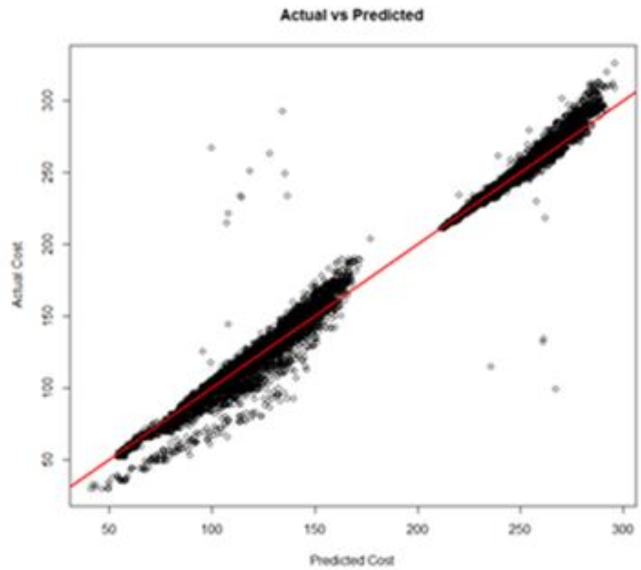


Figure 28. Actual vs. predicted cost values

The Random Forest model was used as a surrogate model for cost estimation enabling designers to quickly evaluate cost for many different tolerance scenarios and compare the results with the output of the performance analyses.

4.5 Cost vs. Performance Application

Once both cost and performance surrogate models were created, a study of these analyses could be performed as one application of these tools. By having surrogate models the team was able to analyze a large number of the costing scenarios and how those scenarios would affect the performance of the part.

The aerodynamic performance analysis worked primarily with analyzing the effects on the flow capacity of the turbine. This analysis does not result in a Margin of Safety (MoS), but rather flow capacity variation about the nominal. More variation in the flow capacity results in lower performance and can have damaging effects on efficiency and the engine as a whole. Figure 29 shows a plot comparing the flow capacity variation vs. the cost where each individual point on this plot represents a single cost scenario (refer to Table 8 for scenario examples) and the corresponding flow capacity variation.

Figure 29. Aerodynamic performance vs. cost comparison

The red dot represents the current nominal part that the team was working with during the development of this methodology. The green line represents the Pareto front developed from this analysis for purposes of optimization.

The structural performance analysis investigated multiple different performance metrics (fatigue, creep, strength, etc). These metrics all had MoS based on a set of requirements. A lower MoS corresponds to a lower performing part and a MoS of less than zero results in not meeting requirements. Figure 30 shows a plot comparing the minimum MoS vs. the cost. Each individual point on this plot represents a single cost scenario (refer to Table 8 for scenario examples) and the corresponding minimum MoS (of the 12 analyzed).

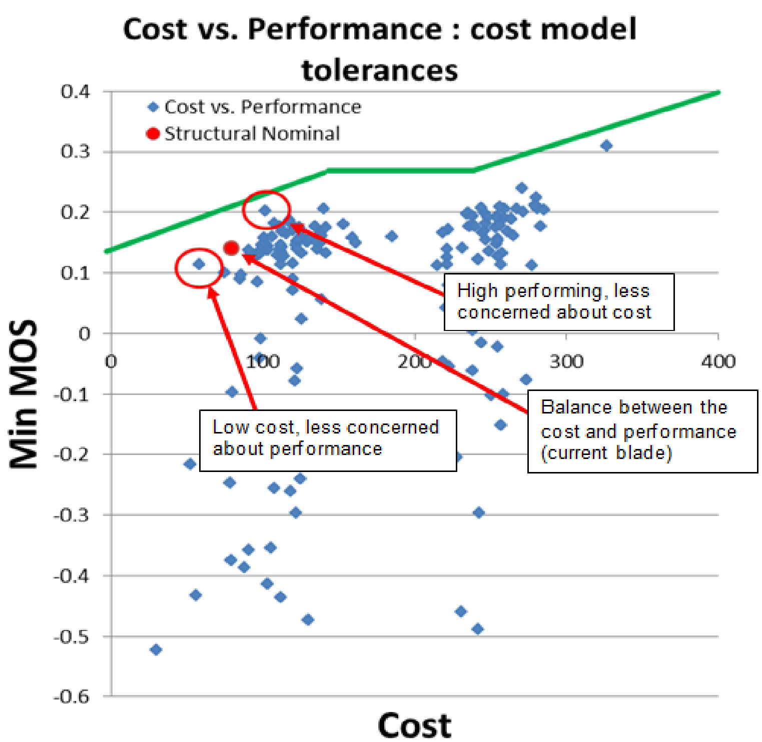


Figure 30. Structural performance vs. cost comparison

The red dot represents where the current nominal part that the team was working with during the development of this methodology. The green line represents the Pareto front developed from this analysis for purposes of optimization.

Previously, a few options might have been presented to a designer to make decisions on which tolerance scenario and design to choose, but now depending on the customer, the goal of this product might be:

- High performing, less concerned for cost
  - There is a large set of scenarios that can be analyzed and be able to not only get a higher performing part, but a higher performing part with less of an increase in cost.
  - Refer to the plots, there are many options to get lower flow capacity and higher MoS, but the two highlighted high performing parts give you the largest increase in performance for the set increase in cost. This is insight previously unobtainable.
- Low cost, less concerned about performance
  - There is a large set of scenarios that can be analyzed and be able to not only get a lower priced part, but it gives you options that would give the customer the biggest cost savings with limited effects on performance.
  - Refer to the plots, there are many options to get lower cost, but the two highlighted low cost parts give you the largest cost reduction while sacrificing limited amounts of performance. This is insight previously unobtainable.
- Balance between the cost and performance
  - Now there is a large set of scenarios that can be analyzed and be able get the perfect balance that matches specific needs.

With the customers end goal and criteria in mind, Design and Manufacturing can make educated decisions on this part that addresses both cost and performance in a clear way. By having both cost and performance data, cost reduction efforts and optimized new designed are made possible.

This is one application of the data generated by the methodology described in this project. Once this data is generated, it can be applied as the end user needs it to, but it is because of this project and methodology that these tools can be generated to have easier access to this data to apply it as needed.

4.6 Demonstration of Advanced Analytic Work on the DMC

The primary focus of this task was to have an automated thread that can be demonstrated on the Digital Manufacturing Commons (DMC). The DMC is a web based interface that allows for accesses to applications that can be run why anyone with an internet connections. By demonstrating capability on the DMC using a Microsoft Surface Pro 4, this project has created an avenue for this analysis to be run in real time by Manufacturing and Design. This portal will give Manufacturing and Design a common communicational ground to access and share the data developed with this methodology. It also does not require the end user to have the licenses required by the analysis in order to view the results saving license costs while having access to key information to optimize component design and make. Development of the DOME services, integration between the DMC and the individual modules, and HPC capability was done by National Center of Supercomputing Applications (NCSA). The creation of the individual analysis modules were done by Rolls-Royce, ASDL, and ARL.

4.6.1 Developing the DOME services and integration of the modules

In the original scope of this project included the creation of a copy of DMC running in the NCSA cloud and using the NCSA high-performance computing (HPC) systems to run projects from the other partner institutions. During the review of the DMC product and the interaction with its development team it was determined that the proper path forward was the use of the main DMDII DMC instance with the sharing of data pointers rather than a full build of the DMC. These pointers would point to files and modules on NCSA's iForge HPC environment. With this method, it required informing the overall connections and building the workflows and operations to support the 3 different modules of the project – aerodynamic performance, structural performance, and cost prediction. Each of the individual systems would require operations that included pre-processing, operation on the HPC system and post-processing for the user. Automating this process was the primary concern for NCSA in the project.

The system itself was a rather simple step forward from the initial plan for project. Instead of rebuilding the DMC, NCSA built a web service to collect data sets and provided a Lightweight Directory Access Protocol (LDAP) based authentication model to support limits on who can view and add new data sets to the system. In addition, NCSA built Java-based DOME services to support the connection to DMC for each of the 3 workflows. Figure 31 shows the overview of the work done by NCSA.

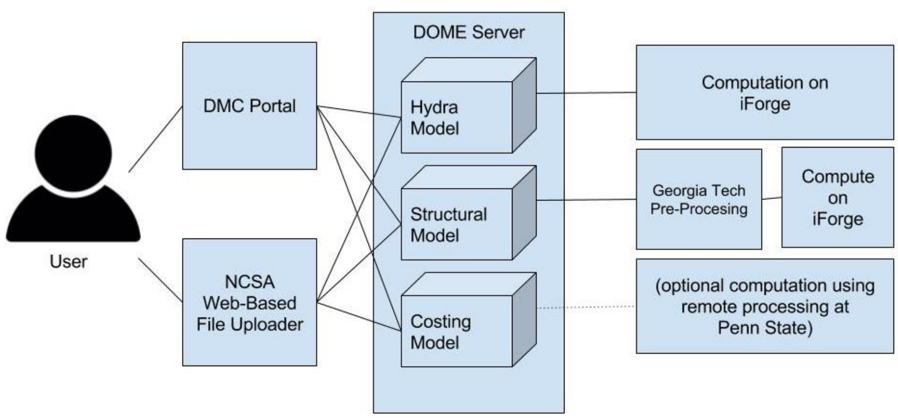


Figure 31. System architecture with integration on the DMC

To keep data privacy as a primary concern in the project, the web server was built to a standard authentication method to support the control of the data. This system running within the NCSA cloud was developed to collect data with ease from the eventual users of the system. A simple drag and drop interface was created with a web front end so that users could input data quickly and easily from wherever they were working. The system then produces a URL pointer to the data that was used to start jobs from the DMC. In addition, the system was expanded to allow jobs to run instantly as needed without using the DMC interface. The methods to move the data and begin operations took place as part of each of the workflows, and the data was stored on the web server until a request to run jobs on it was started. This request could be from the local system or the DMC. From the point of starting the job data was moved to other services to run calculations and a URL for final output would be created. For each of the methods a URL was created to allow the user to view the results of their data operations. This URL could be sent back to the DMC and would require the user to authenticate to view the results. Results were provided via a web interface and could be downloaded for further analysis.

Each of the developed workflows was created as a separate application in the systems. As they were built NCSA looked at the operations as a user would implement them and structured the workflow to follow those steps. With each workflow there were specific instances of unique solutions, this might have been an extra step running in a Windows environment or a system that required applications with significant completion times. To handle this operation NCSA completed a simple message service that could track progress of workflow steps and only the final result would be sent to the DMC. This solution is of key importance for applications that would have unknown runtime at start. With many of the HPC solutions we expected 30-40 minute runs for multiple steps of the workflow. In addition, each workflow would require more options to monitor that workflow than were available in the DMC. To test this a full status page was built for the interaction of a single workflow. This system would show status and ongoing operations. This was a benefit to the user, but required a significant effort to implement for each workflow. Without a method of longer-term automation this would not work for the application in the future.

For this project the system was built with the idea that a user with Windows Surface tablet could from anywhere submit a set of files to the application and output results describing the changes in a model and the cost those changes would require. This was intended to be a process that would be quick and allow for shop floor manufacturers to have access to this data within a few minutes. For this specific application, the structural and aerodynamic analysis took as long as one hour, which is slow for someone on the shop floor (refer to the Future Work and Improvements section for other options). That being said, for operations that users were implementing on a regular basis and might not have the licenses required for the analysis, the benefits of the automated workflow through the DMC is a huge benefit.

5 ACCESSING THE TECHNOLOGY

The methodology developed by this project used the following software and systems:

- Geomagic Foundation 2015
- RRC Proprietary Software (Refer to Background IP below)
- NESSUS Response Surface Toolkit v1.3.1
- NESSUS v9.8.
- Salome v7.8.0
- NX v10.0.3
- ANSYS
- aPriori
- iForge

This methodology is not dependent on using these specific software and systems; it can be used with other commercially available software and tools depending on the applications.

6 INDUSTRY IMPACT & POTENTIAL

The methodology developed in this project can be applied to any design and manufacturing team who is interested in optimizing the cost and performance of a product. This project was not aimed to affect only one market or industry, but to create a framework for the engineering industry as a whole to improve their methods of quantifying a cost to performance comparison. In order to use this methodology, the company or team will need to develop the individual tools.

This methodology has numerous applications once implemented for a specific component; the following are a list of a few:

- Multiple Applications
    - This methodology can be applied to various applications not related to gas turbine engine components, as long as the analytical tools are put into place based on this methodology.
    - Additionally, this can be applied to both aftermarket and new designs. This methodology was proven by the use of 100 as-manufactured blades, but used processes that can be manipulated to take in parameters as well. In the aftermarket the user would be primarily focused on using as-manufactured parts for production support, cost reduction, validation, process improvements, service analysis, etc. For a new design the user would be primarily focused on using parameters based on the feature's dimensions and tolerances to determine the performance variability as a result of manufacturing, design improvements, cost reduction, etc.
- Cost Savings
    - By enabling a quantifiable comparison between the cost and performance of a component a design can be optimized to produce the most cost effect part to meet customer needs. This cost savings is applicable to both aftermarket and new designs. By developing a workflow that demonstrated capability of a parametric

model and as-manufactured parts, this project has demonstrated that regardless of where the component is in its lifecycle this methodology can be applied to have possible cost savings.

- Better Performance and Reliability

  - By developing a workflow that analyzes as-manufactured parts in an automated fashion, the performance variation can be determine prior to ever being implemented into service. This visibility will improve the design by giving a large amount of performance scenarios that will enable an optimized design to increase service performance and prevent failures in the field.

  - Additionally, with a proper cost vs performance analysis a large portion of the design space can be analyzed which can result in an improvement in performance without sacrificing cost. This performance boost can elevate the life cycle cost of components and provide cost and performance benefits at the same time.

- Improved Engineering Producibility

  - By streamlining the analysis process of as-manufactured parts, engineering has quick and reliable analysis visibility that will allow for quicker and more justifiable disposition of parts that are beyond specification. Currently, extrapolations from nominal design or hand calculations are typically used for justification of non-conforming parts, but with this automated analysis there can be a clear correlation between the nominal and the nonconforming part in an hour. This will improve the time associated with the design review process, while also giving more reliable results and could result in acceptance of a nonconforming part that might previous have been reject (cost savings) or prevent a nonconforming part from entering service that negatively affected performance (reliability improvement).

  - With continual performance verification this can further guide future improvements to designs as data from the field on these analyzed parts which will give additional experience to be considered for design improvements. Instead of assuming what the initial state of a failed blade was, by enabling quick performance analysis during production, the as-manufactured variation can be captured and a more accurate representation of the initial state of a failed blade can be determined helping failure analysis in coming to a resolution.

  - With improved communication of critical features between design and manufacturing, improvements to the process can be made in order for manufacturing to focus on what is important in getting a reliable part. The visibility this information will help manufacturing work more efficiently to tackle issues that arise during production.

The above applications and potential improvements are just a few of the benefits from this methodology. Depending on how it is applied there can be many more. This methodology is an enabler for cost savings by understanding the quantifiable tradeoffs between cost and performance, improving the performance and reliability of designs by understanding the performance variation of the as-manufactured parts, and allowing for more efficient and accurate engineering producibility.

7 FUTURE IMPROVEMENTS AND IMPLEMENTATION

At the completion of this project there were the following key areas of future improvement prior to implementation:

1. Improve automation to run entire process through one system.

    a. The modules which are a part of this methodology are all automated separately (aerodynamic analysis, structural analysis, and costing analysis) with varying methods of automation.

    b. Improvements will be needed to the automation and the transfer of data in order to make this process more robust.

    c. Some of these issues are described in Section 4.6.2 and Section 11.5.

2. Continue to work with current manufacturing (in-house and suppliers) to refine costing metrics to get more accurate representation from the costing analysis.

3. In order to implement this kind of methodology into a production setting, an understanding of the frequency of this analysis and the resulting storage required. In a production setting continuous results will result in abundant amount of storage required and ensuring the storage capability is in place prior to implementation is key.

4. This project used 100 blades for the development of this methodology. This number was chosen because it is greater than 30 (typical industry standard for capability) and economically feasible. Future applications could use more or less than 100 blades. The more samples will result in a more statistically representative population, while fewer samples will result in coarser results. The DMDII 14-08-01 team recommends a bare minimum of greater than 30 components, but recommended 100 or more.

5. Modifications to Geomagic Control scripts to improve the meshing of as-built parts

    a. Refer to the “Lessons Learned” section for specifics on this topic

    b. In short, 4 out of the 100 as-built blades failed to converge in the structural analysis. It was determined that this was due to some of the surfaces created by the Geomagic Control script. Improvement to the watertight mesh need to be made.

6. Modifications to Geomagic Control scripts to output the metrology of the as-built parts

    a. This additional step will result in additional data and verification of the work that was done. Also, this metrology could allow for inspection an inspection process to be done during the process.

7. Re-run aerodynamic analysis with a tighter mesh in order to improve variation probabilistic on the double passage analysis.

    a. Refer to the “Lessons Learned” section for specifics on this topic

b. In short, during the probabilistic analysis of the double passage aerodynamics, there was a large amount of scatter that prevented a surrogate model from reliably being developed. This is primarily due to the mesh size that was chosen for the analysis to improve run time and prevent additional computational resources.

8. Developing an additional workflow into this system to allow to continuous updates to the models.

    a. One of the current barriers to full adoption is that the analysis runs (aerodynamic and structural) take roughly an hour to run, which is good from an analysis standpoint but slow for manufacturers working on the floor.

    b. Creating a large sample of components upfront (>100 components) and doing the analysis to get a good statistical surrogate model. Then creating a sampling plan to increase data point within the surrogate model as the product matures.

        i. This sampling plan will not only help flag any performance shifts in the future, but will keep the surrogate model up to date and get a large sample size during production.

    c. This additional opportunity would enable a surrogate model being used in a rapid manor by manufacturing and design (through the DMC in a matter of minutes rather than an hour), while still getting statistically sound results that are based on real as-built analysis.

        i. The surrogate model would need to be thoroughly verified before becoming a gold standard, but this is an opportunity to improve the speed of decision making until computer capability improves.

These are the key improvements that were determined based on this single application. By applying this methodology to other components, this framework that was created can continue to be improved to improve the methodology for other applications.

8 CONCLUSIONS/RECOMMENDATIONS

In order to tackle long standing problems between the design and manufacturing chain, a digital thread based methodology was created by this project in order to:

- Improve product performance/reliability
- Reduce costs
- Improve engineering productivity

The methodology created by this project successfully accomplished the required tasks below, by the following:

1. Capture geometry of as-manufactured parts for analysis
    a. Developed an automated workflow using 3D Systems software to turn a 3D geometry scan of an as-manufactured part into a workable solid that can be used in performance analysis. This automation took a process that previously took hours and reduced it to a process that takes a few minutes.
2. Predict as-manufactured aerodynamic performance
    a. Created an automated workflow that will input a geometry file which goes through a pre-processing geometric handler cleans the geometry getting it ready for analysis and extracting geometric design parameters, a meshing tool creates a quality mesh for the CFD, boundary conditions are applied based on nominal analysis, a CFD solver is run with a high performance computer, and finally a post-processor calculates the desired aerodynamic performance parameters. With this automated process, aerodynamic analysis is able to be run by designers and manufacturers to analyze the effects of the as-manufactured parts without additional effort from an analyst.
3. Analyze variation in aerodynamic performance
    a. With the use of the automated aerodynamic tool, an analysis on the variation of the as-manufactured parts is possible in order to understand the variation of the parts being produced out of the manufacturing process. With this variation a surrogate model was generated in order to facilitate a cost vs. performance comparison to be performed.
4. Predict as-manufactured structural performance
    a. Created an automated workflow that will input the workable solid generated by 3D Systems software and pass through a name selection process in order to be meshed and processed through ANSYS for structural analysis. This process allows structural performance analysis to be performed on as-manufactured components with little to no interaction by the end user.
5. Analyze variation in structural performance

a. With the use of the automated structural analysis tool, an analysis on the variation of the as-manufactured parts is possible in order to understand the variation of the parts being produced out of the manufacturing process. With this variation a surrogate model was generated in order to facilitate a cost vs. performance comparison to be performed.

6. Evaluate impact on manufacturing costs

   a. Generated new tools in order to calculated the "should-be" cost of a component based one features instead of individual surfaces. This new method allows for a direct comparison between cost and performance in order to determine correlations and trends for quantitative decision making for optimizing a design based on cost and performance. With this tool a study was performed on the cost vs performance in order to determine possible cost saving measures and performance enhancing features to improve the current design.

7. Integrate advanced analysis tools onto the DMC to demonstrate capability

   a. By integrating the advanced analytical tools with the DMC, there is a central system that can be used to pass analysis results between manufacturing and design which bridges the silos that are currently created in the manufacturing and design fields. This communication and easy access to the performance and cost associated with the part will allow for a more productive design and make team.

This methodology was created by developing tools specific a single turbine blade application, but can be applied to many other applications. With the implementation of this methodology in other industries and applications, it will have the following benefits:

- Reduced cost of production and cost of ownership by leveraging knowledge from true manufacturing variability and process capability.
- Integration of HPC and data analytics to enable impact assessments of as-manufactured variability on component performance, maintenance, and integrity.
- Breaking down barriers across the supply chain by having secure (ITAR compliant) transfer of data between manufacturing and design via the digital highway and HPC capabilities.
- Access to manufacturing variation on performance and cost allow for enhanced productivity that will allow for tradeoffs and creating an optimal design for the customer.
- Technological advancement and automation created by this project will guide further innovations to better educate the next generation of workforce.

From this methodology there were many future improvements and potential future impacts recognized. These include:

- Modification to the Geomagic scripts in order implement a 100% conversion accuracy that be able to extract additional information to better guide design and manufacturing communities under the same system.

- Improvements to the automation methodology and tools will improve the robustness of this process to enable a single system approach.
- Implement in production with the use of surrogate models and sampling in order to improve the speed of results for quicker decision making opportunities.
- Continue to incorporate the latest knowledge of current manufacturing processes to create more accurate costing analysis to find more representative cost savings.

This project focused on one application and in order to continue improvement to this process, additional applications will need to be explored with additional projects and implementation into the design process.

Overall, this project successfully accomplished its primary goals. By developing a method to quantitatively compare both cost and performance, manufacturing and design can find common ground in order to quickly and effectively develop the optimal design without compromising cost or performance and develop solutions to successfully solve the customers' requirements. With the use of advanced analytics and methods development, this methodology will help keep U.S. industries competitive, when applied to many different applications.

9 LESSONS LEARNED

During the development of the methodology described in this report each task faced its own set of challenges. From these challenges, our group had a set of lessons learned which are described below.

9.1 Capture Geometry of As-Manufactured Parts

- Any hardware being used for DMDII projects should be included in the proposal to eliminate the need to borrow from production stock.
    - In order analyze the performance of as-manufactured parts, a selection (100 blades) of parts needed to be acquired in order to be scanned. Since the original proposal did not include this, there was a 4 week delay in this portion of the project because of the difficulty in borrowing the required set from production stock. By accounting for this up front, it will allow for the production to adjust in order to access the hardware required.
- Converting the 3D scan into a parametric model using 3D Systems' Design X Software was not the most appropriate model for this task.
    - During the training provided by 3D Systems' applications engineering team the team was exposed to the entire suite of tools at disposal. The initial intent was to use the Design X Software for this task, but after gaining exposure to the Control and Wrap (which allows for a parasolid to be created instead of a parametric model) it was determined that these tools would be more appropriate because it would give a direct representation of the component instead of parameterizing the part.
- Aligning the components based on the assembly datum structure instead of the best fit between the models and scans, produced better results.
    - The initial Control script aligned the parts based on a best fit comparison which aligns the 3D scan in X, Y, and Z space to have the least amount of variation between it and the 3D CAD model. Using an initial set of 10 blades, 6 of those were created into unusable solids that had surface errors preventing them from being implemented into the structural analysis. To correct this issue, 3D Systems set up as-built 3D scanned blade in X, Y, Z space using Rolls-Royce nominal blade model's three defined datum plane surfaces utilizing 3D System's Control program, then performed auto-surfacing operations within the Wrap program as was previously done. These 10 test blades were re-run using this new process and the surfaces were found acceptable with no errors. This new process of doing an alignment based on the datum structure was used for the remainder of the conversions.

9.2 Predicting As-Manufactured Aerodynamic Performance and Variation

- Surrogate model for an aerodynamic double passage analysis requires a finer mesh.

- During the creation of the double passage surrogate model, it was apparent that there was a large amount of scatter within the results produced from the CFD analysis. When performing the analysis a coarser mesh was used in order to provide quicker results and to not require additional computational resources. From this project it was determined that only single and double passage analysis is required to represent the full annulus, but in future use of this tool a finer mesh should be used in order enable a double passage surrogate model to be created. The finer mesh will result in less scatter within the data, but will require more time in order to perform the analysis. Details on the correlation of the model generated can be found in the Appendix A.

9.3 Predicting As-Manufactured Structural Performance and Variation

- Discrepancy between the as-designed geometry model and the template to generate the as-built geometry models.

  - The boundaries of surfaces between the two geometries barely match up. An example is shown in the Figure 32. The ANSYS Workbench models define boundary conditions and gather results based on the surfaces. As a result of the discrepancies, the result gathering in certain regions with severe discrepancies returned non-comparable results and were abandoned. The cover plate attached to the blade was modeled as a point mass in the ANSYS models and its location was based on boundary of the surfaces. Due to the discrepancy, some of the results show a few percent difference between the as-built and as-designed models.

    In the future, when the template for as-built geometry models is generated, the key surfaces of the as-design geometry should be identified and their boundaries mapped to the as-built geometry template.

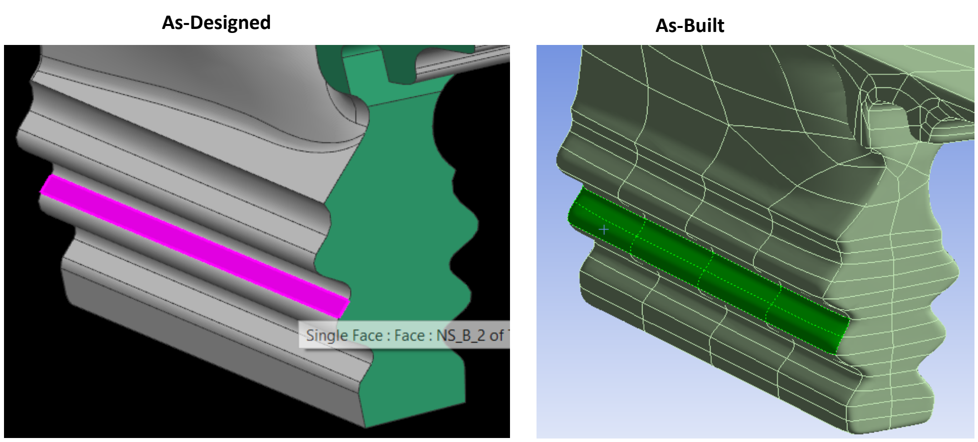


Figure 32. Example Discrepancy

- Geometry corruption and difficulty in meshing

  - For the one hundred as-built blade geometry models received from 3D Systems, Rolls-Royce conducted an automated meshing test. Thirty-five of the one hundred as-built blades failed to mesh due to poorly defined faces and holes in shroud and platform regions. ASDL repaired the holes in the as-built geometric models. However, a few of the faces in the shroud and platform regions of the as-built template are still poorly defined and lead to meshing failure and bad elements in four of the as-built blades. An example of a bad face is shown in the Figure 33. In the future, approaches to generate better geometry models and better automated geometry repair approaches should be investigated to avoid meshing failures.

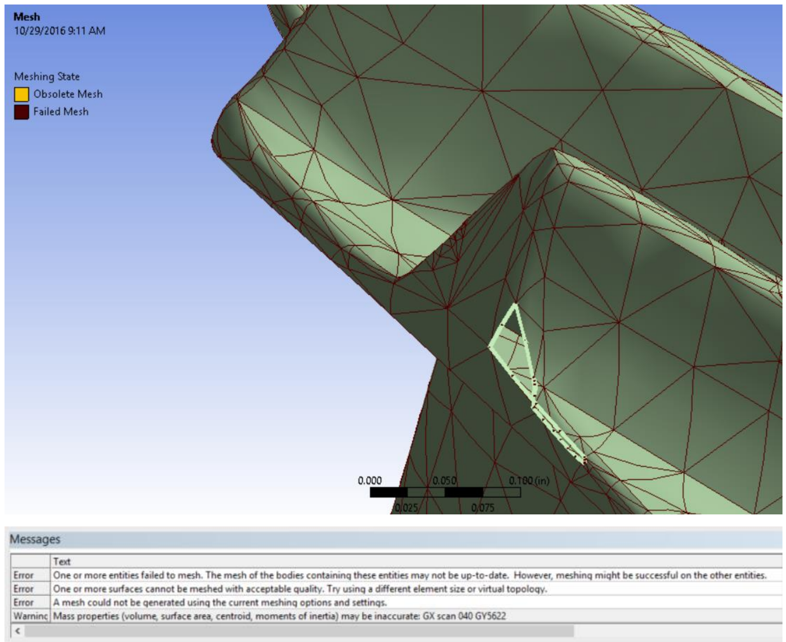


Figure 33. Example Failed Mesh

- Geometry difference at the stalk edge

  - Significant differences in maximum stresses in platform and stalk between the as-built and as-designed models were discovered after both models were fine tuned. Further checks on geometries of the as-built and as-designed models were performed and significant differences in a geometry features were discovered. The edge of the back stalk, where the maximum stalk stress occurs, in the as-designed model is sharp. However, this edge in all as-built models is rounded off. The difference is shown in Figure 34. The differences in geometry lead to significant differences in the maximum stalk stress results and also affects the nearby maximum platform stress results. Rolls-Royces obtained an actual blade and it has sharp edge at the back stalk. This means the sharp edge was lost somewhere in the process scanning the as built blades, fitting surfaces over the GOM data, or from the actual casting process of the as-built part themselves.

    In the future, better geometry scanning or surface fitting approach may be necessary and should be investigated.

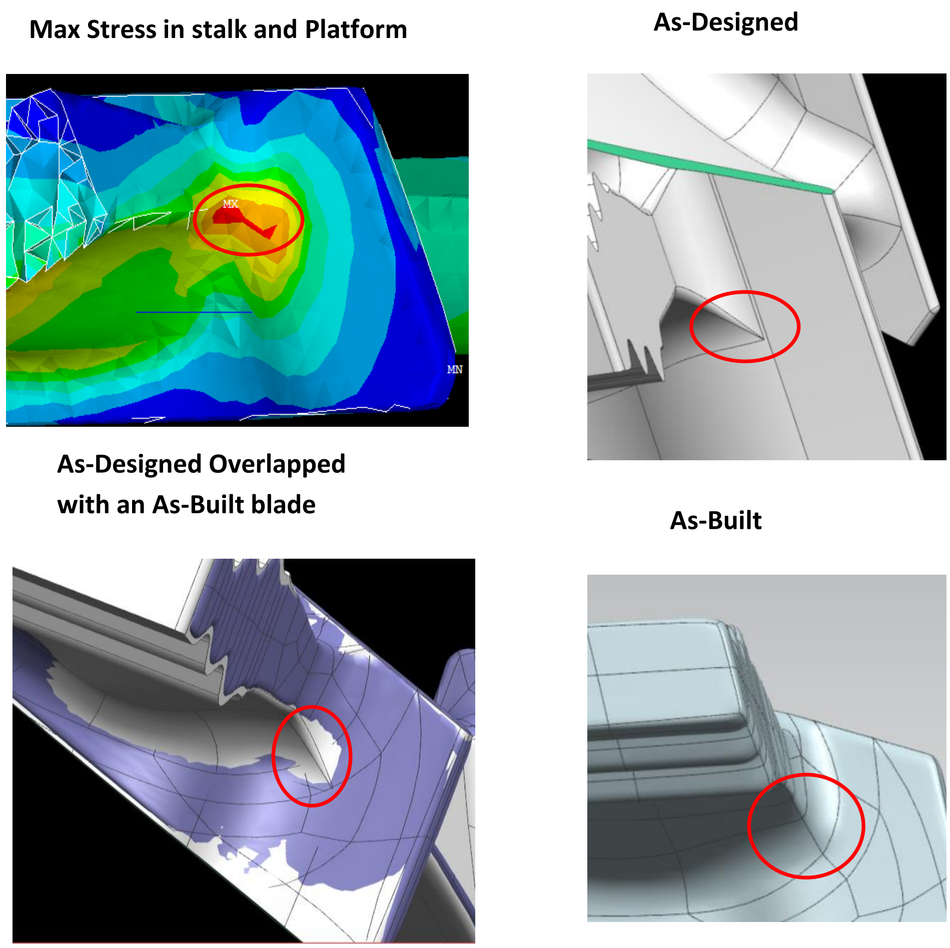


Figure 34. Geometry Difference at Stalk Edge

- Regeneration failures in NX parametric model/Paramaterized model limitations

    - Certain combinations of some parameters caused geometry regeneration failures in the NX parametric model during geometry parameterization. An example is shown in the Figure 35. The failed cases were discared and the surrogate models were built based on successful cases. This cause the structural analysis to be run with values of 110% of the print tolerances and below.

      Further investigation to improve the robustness of the NX parametric model may be desired in the future.

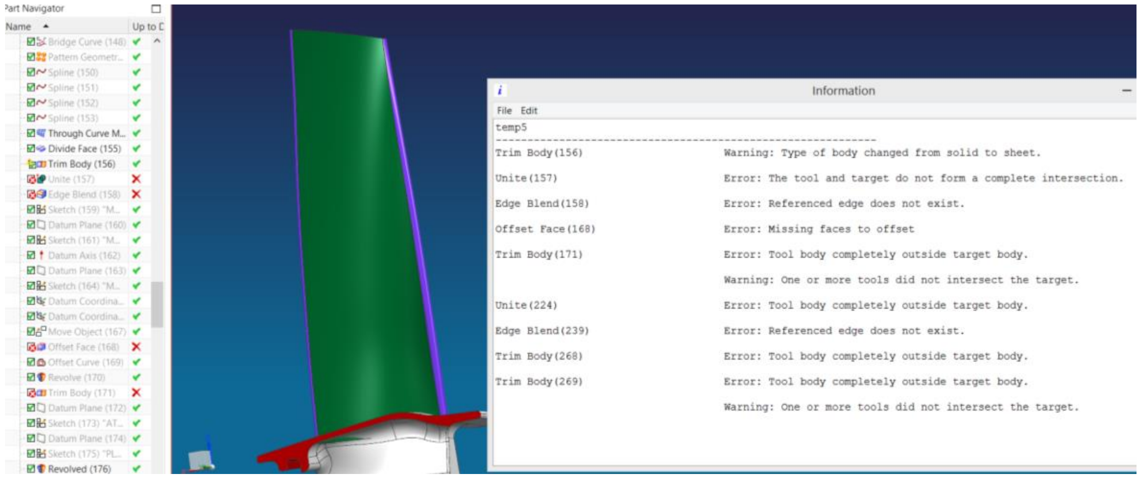


Figure 35. Example NX Regeneration Failure

- Issue in post processing approach to gather max airfoil stress.
  - While max stresses in other sections were fitted well, the max airfoil stress data from the DoE cases shows great randomness. During further investigation of the physical model, it was discovered that the max airfoil stress was gathered by coordinates, while other sectional max stresses were gathered based corresponding geometry features. This approach gathers airfoil stresses for nodes between the lowest point of top airfoil fillet and the highest point of the airfoil hub for further calculation. It cuts through geometry feature based stress distributions, which vary with parametric geometry changes. An example is shown in Figure 36. This leads to significant randomness in max airfoil stress data among the DoE cases in the selected region.

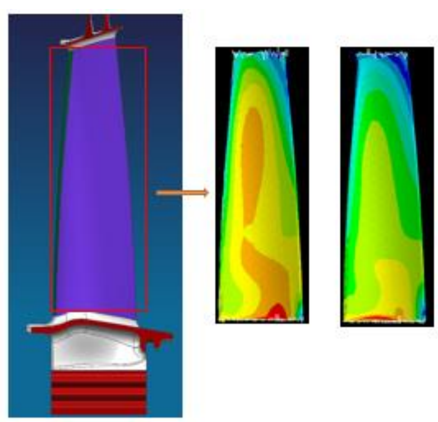


Figure 36. Max Airfoil Stress Gathering Approach

This randomness caused surrogate model fit failure for max airfoil stress and for MS strength and MS LCF in airfoil, which are directly calculated using max airfoil stress. The randomness is averaged in the ten cross sections in the MS creep calculation and does not significantly influence the surrogate model fit for MS creep in airfoil. Replacing the post processing approach was discussed, but it required rerunning all as-built and parametric as-designed cases to keep consistency. This would result in weeks of delay for the project schedule. After discussion with Rolls-Royce, the max airfoil stress and related responses were excluded from the further study.

Geometry feature based approaches to gather max stress is considered to be a better method for surrogate modeling rather than coordinate based approaches, or a buffer zone should be considered if a coordinate based approach is used in the future.

- Oversimplification issue for calculation of MS creep in shroud

  Simplified modeling and post processing approaches are used to speed up calculation for this demonstration project. However, a simplification leads to non-realistic creep calculation for the shroud. The actual temperature distribution in the blade is simplified to sections of uniform temperature and the shroud section has the same temperature. Since creep is calculated by stress and temperature, the critical creep region in shroud shifts from where it should be, to where the max shroud stress is located, as shown in Figure 37. The surrogate model for MS creep in the shroud shows a good fit, but is not the realistic. After discussions with Rolls-Royce, it was excluded from further study.

  In the future, replacing this simplification with a production approach (higher fidelity temperature distribution and calculate nodal creep for each node) should be considered to provide a more realistic MS creep in the shroud.

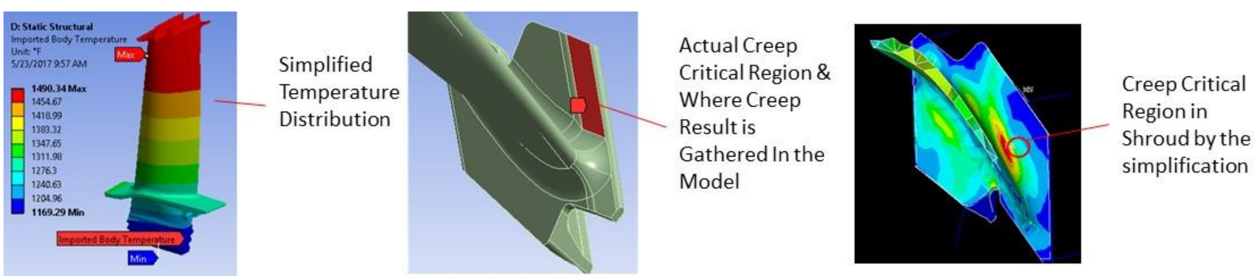


Figure 37. Critical Creep Region in Shroud shift by Simplification in Temperature Field

9.4 Manufacturing Cost Analysis

- When binding surface tolerance, adjust for additional feature tolerances that result
  - When creating a feature based tolerance cost analysis special care must be taken when working with features that are based on two surfaces, for example a shroud thickness. Using the method described in this report, one has to be aware that using a surface tolerance on both surfaces that define the width of the feature will result in double the tolerance. See Figure 38 for a visual representation. This double tolerance needs to be adjusted when performing cost analysis in this way.

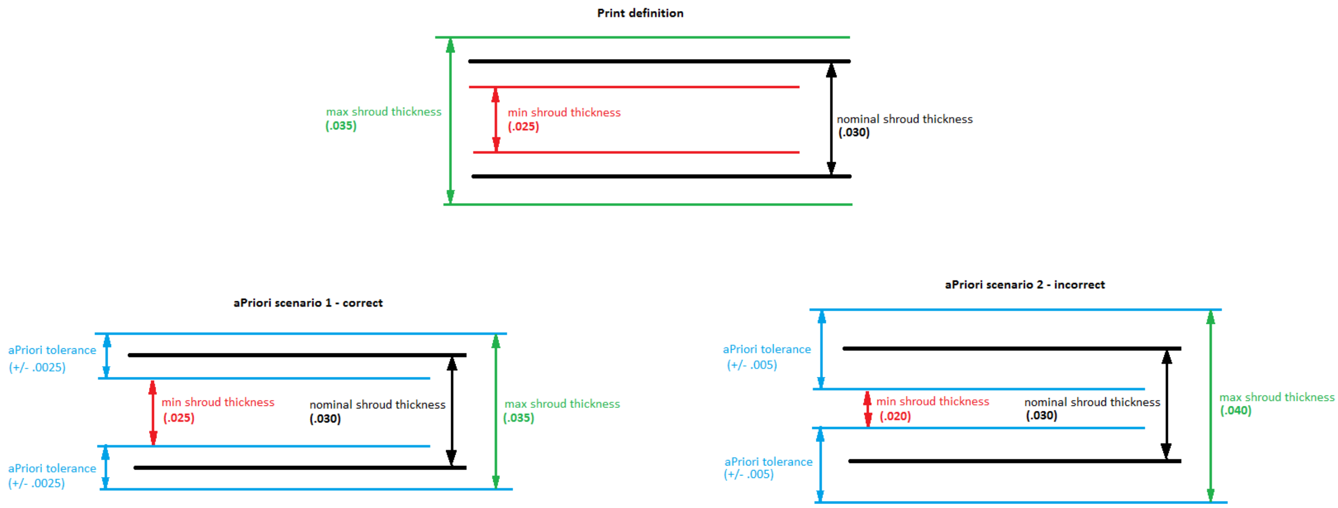


Figure 38. Costing analysis consideration to prevent double tolerance on a feature.

9.5 Demonstration of Advanced Analytic Work on the DMC

- NCSA's iForge HPC cluster is Linux based which prevented full automation through one system.
  - Since iForge was Linux it prevented four programs (that were Windows only) from being run on the HPC cluster. These included:
    - Rolls-Royce's geometry processor (used in aerodynamic performance analysis)
    - Geomagic Suite (used in structural performance analysis)
    - Salome (used in structural performance analysis)
    - NX (used in structural performance analysis)
  - Because of this, instead of run each module through one system starting with a 3D scan .stl file there were modifications made to the automation that are not as robust moving forward.
  - The aerodynamic performance required an analyst at Rolls-Royce to generate a blade definition file (converts the stl file to a blade definition file) before passing it through the cluster. This is not ideal because we want to eliminate the need for an analyst to run this and the licenses required for this step.
  - The structural performance required the stl file to be passed from NCSA's cluster to Georgia Tech's servers in order to perform the preprocessing steps. This is not ideal because it will require more resources to pass the data back and forth and make the process less robust with more handoffs.