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ROBUST LIFECYCLE OPTIMIZATION OF TURBINE COMPONENTS USING SIMULATION PLATFORMS

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Abstract

In early phases of turbofan engine component design, simulation is favored since it reduces the need for expensive physical testing. However, deterministic simulations for model validation do not consider uncertainty at all. Uncertainties can be classified into three types: aleatory uncertainties, epistemic uncertainties, and error. In this paper, we investigate the potential of a multidisciplinary simulation platform to address these uncertainties and errors for a given test case.

We place specific focus on the geometry assurance of a given turbofan component - the Turbine Rear Structure (TRS). Simulations are generally performed based on nominal geometries, materials and loads. However, when a product is mass-produced, each realization of the product design will deviate from the nominal geometry. By generating CAD models from scanned 3D-data of manufactured parts and running them through the simulation platform, the effect that geometric variation has on aerodynamic and structural performance can be investigated. Further, by moving the reference points in a virtual assembly process, we can, to some extent, suppress the effects that this variation has on aerodynamic and structural performance.

From a technical point of view, the suggested approach means a significantly improved ability to numerically simulate and optimize robustness of component designs with functionality criteria from principally different disciplines. From an industrial application point of view, the suggested approach provides a tool for including part variation in the early design face, rather than being treated downstream in the development process.

1 Introduction

A product whose function is insensitive to geometrical variation is defined as functionally robust [1]. In aero engine applications, functional robustness is often related to physical phenomena that are coupled. The example given in this paper is the thermal stress stemming from the heating of a turbine structure during flight. Since this problem is dependent on the geometry at hand, it is straightforward to realize that geometrical variation will affect structural strength, which will have an effect on product life length. However, geometrical variation will have another indirect effect as a change in the aero surface will affect the convective heat flow into the material, resulting in a different thermal expansion and life length.

Approaching the above problem requires the use of many engineering disciplines. For a deterministic evaluation of a nominal product, the common approach is for these analyses to be performed in different simulation environments by specialists in each field, with data being manually transferred between them. For robustness analyses, however, this process becomes ineffective and time-consuming [2]. In addition, uncertainties and errors are introduced in the decoupling of the problem.

In this paper, an automated, sequential process is suggested for capturing the problem, which allows for parameterizations to be propagated from one end of the analysis chain to the other. A method of combining different analysis methods into a multidisciplinary simulation platform is suggested. This method is then used to investigate the robustness of a turbine rear structure, which is analyzed with respect to thermal stress as well as aerodynamics and structural strength.

The validity of the simulation platform to produce accurate results is dependent on an array of factors. In addition to uncertainties in the physical reality - geometry, materials and operating conditions - limitations in the fidelity of the simulation model introduces error. If magnitude of these respective errors is understood, we can balance the engineering effort that is put into to the respective steps of the analysis process.

2 Scope of Paper

This paper starts with a technical background. Then, the subsequent frame-of-reference section includes a discussion on the scientific fields of *robust design* and *uncertainty quantification*, how they relate to each other, and why they are relevant to the problem. We also give a brief background to platforms, and multidisciplinary design optimization.

In the problem description, the simulation platform is presented in detail. The two case studies - the fixture optimization and the evaluation against the framework put forth by Oberkampf el al. [3], and – are also presented. We also look briefly at how physics decoupling and mesh resolution affect the results.

The results section gives the results of the case studies, which are discussed in the conclusions and discussions section.

3 Technical Background

The commercial turbofan engines of today are designed to be fuel-efficient. This is accomplished by increasing the bypass ratio, which in turn implies large fan diameters. Modern engines are significantly larger than engines designed 30 years ago. The components inside the engine have also increased in size.

The turbine rear structures in the rear end of a jet engine have a range of functional criteria from various fields of engineering. They need to be able to withstand significant thermal and structural loads. In addition, to optimize fuel efficiency, they need to be as light and aerodynamic as possible. These functionality criteria must be balanced in order to obtain an optimal design.

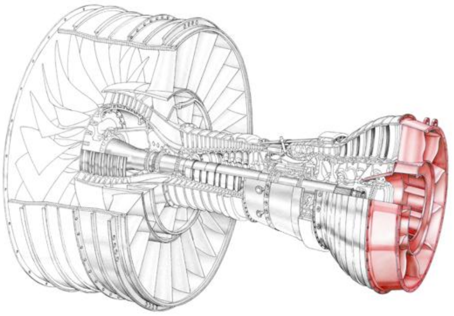

Figure 1: Turbine Rear Structure (marked in red)

However, manufacturability criteria are often difficult to quantitatively assess in the design optimization process. As a result, it is often the case that designs optimized from a functionality perspective are expensive or unfeasible to realize in practice. To avoid this scenario, the functionality and manufacturability need to be balanced in order to find the truly optimal design [2]. One of the key limitations of manufacturability is geometrical variation, i.e. that the dimensions of a manufactured product deviate from the nominal geometry. Geometrical variation occurs at many stages [4]. Deviations in ingoing parts, as well as dislocations when placing parts in fixtures, propagate through the assembly, and ultimately affect the performance of the engine.

TRSs are usually welded assemblies consisting of cast, wrought and sheet metal parts. The ingoing parts all have some degree of geometrical variation. This part variation propagates through the fixturing and welding process into the final assembly. The assembly variation is dependent on part design, placement of fixturing points and welding sequence. By controlling these factors in an appropriate way, assembly variation can be suppressed.

4 Frame of Reference

A lot of scientific work has been conducted on how to deal with nondeterminism. We focus our attention to two (overlapping) scientific frameworks:

On the one hand, there is the robust design methodology[1, 4-11], introduced by Taguchi[10, 11], which aims at minimizing the effects of variation without eliminating the variation itself. The research is often motivated a desire to increase quality and reduce cost in product development, and as such, it is related to Lean Product development [12, 13].

On the other hand, there is the field of uncertainty quantification [3, 14-19]. This research is more commonly motivated as a means to improve reliability in safety-conscious industries such as the aerospace industry [3, 17] and nuclear industry [20].

The distinction between these fields is mostly due to application and context - the underlying principle is the same [17, 19].

4.1 Uncertainty Quantification

There are many different sources of error in simulation. In the field of uncertainty quantification, there is generally a distinction between *aleatory* uncertainty, *epistemic* uncertainty and *error*. [3, 14, 15, 19]

Aleatory uncertainty is also known as *irreducible* uncertainty, *inherent* uncertainty, *variability* and *stochastic* uncertainty. The term is used to describe the inherent variation associated with the physical system or the environment under consideration. It can generally be estimated by a probability or frequency distribution when sufficient information is available.

Epistemic uncertainty is also known as *reducible* uncertainty, *subjective* uncertainty, and *cognitive* uncertainty. It can be defined as a potential inaccuracy in a phase or activity in the modeling process that is due to *lack of knowledge* [3].

Finally, *error* is defined as a *recognizable* inaccuracy in any phase or activity of modeling and simulation that is *not* due to lack of knowledge. This error can be either *acknowledged* or *unacknowledged*.

4.2 Robust Design

Robust design is a methodology for designing products that are insensitive to variation. Robust design methodology was pioneered by Japanese statistician Genichi Taguchi [10, 11]. According to Phadke [7], product variation may stem from raw material variation, manufacturing variation and variation in product usage. Robust design aims at suppressing the effects of this variation without eliminating the variation itself.

Robust tolerance design deals with geometrical variation in parts, fixtures and assemblies. A geometrically robust design is defined as design that fulfills its functional requirements and meets its constraints even when the geometry is afflicted with small manufacturing or operational variation [4]. Therefore, how much variation in the assembled geometry that can be accepted depends on the functional requirements of the product. Geometrical robustness can be divided into three categories: part robustness, assembly robustness and functional robustness. [21] The factors that define these characteristics and how they are related are visualized in Figure 2.

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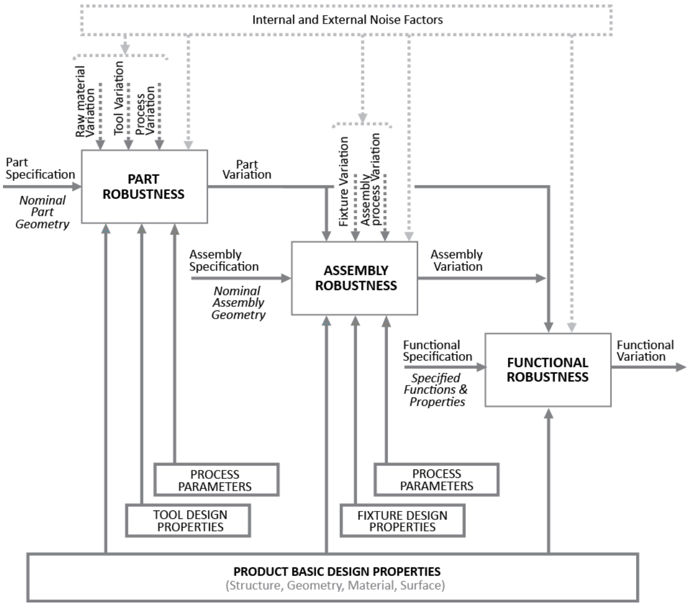


Figure 2: Geometric robustness can be divided into three groups: Part robustness, assembly robustness and functional robustness. [21]

We conducted two previous studies on this platform, one [22] that investigated the effects of assembly variation by applying variation in fixturing points, as proposed by Söderberg et al. [4], and another that investigated part variation [23]. The work presented in this paper build on these prior analyses, and puts them in the framework proposed by Oberkampf et al. [3].

4.2.1 Locating Schemes

The purpose of a locating scheme is to lock a part or a subassembly to its six degrees of freedom in space. Figure 3 shows an orthogonal 3-2-1 locating scheme. The points in the upper right body, the so-called *A-points*, control three degrees of freedom: translation in Z, and rotation around X and Y. The two points in the lower left figure, the B-points, control two degrees of freedom: translation in Y and rotation around Z. Finally, the C-point in the lower right figure controls the translation in X. [6]

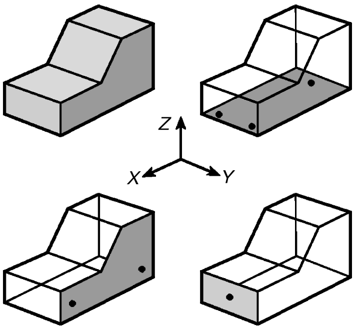


Figure 3: 3-2-1 locating scheme

When attaching a part to an assembly, all six degrees of freedom need to be locked. The part's local positioning scheme, or local p-frame, should be matched by a target p-frame, as shown in Figure 4.

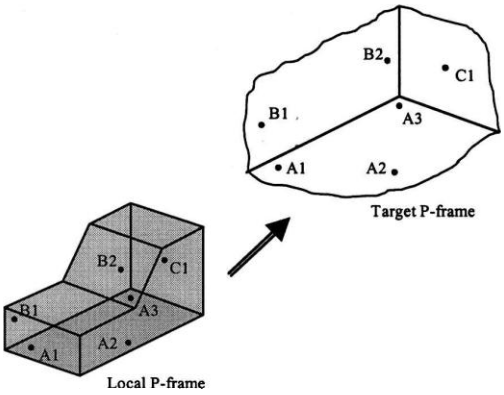


Figure 4: Positioning of a part

Applying variation to the locating points will then affect the positioning of the parts, and therefore, the selection of locating points should be made to minimize the effects of variation on the part position stability [4]. Automated ways of optimizing locating schemes have been put forth [24], as well as methods for optimal allocation tolerances on these locating points [25].

4.3 Platforms

Using product platforms as a means to reuse knowledge in the product design phase have received a lot of attention the past few years [26]. It is seen my many as the silver bullet to beating the competition. The traditional definition refers to the reuse of parts, but custom products with low series, such as aerospace engines is not a product suitable for sharing components straight off. The reuse has to be found elsewhere. The reusable knowledge blocks from technology development is an example of that, often concluded as technology platforms. In literature technology platforms are described in a context to meet challenges regarding a diverse product portfolio where components cannot be reused [27]. Consequently, one such technology could in fact be simulation technologies that are reused throughout the organization, and across project borders.

The benefits of platforms are rigorously examined in research [26] and depend not on definitions in theory alone, but also on how the platform effort is supported and how that support is implemented. For long, IT-tools have been the way to manage knowledge and knowledge reuse [28]. The implementation of technologies in IT-systems is an efficient way of ensuring a correct reuse of the technology.

4.4 Other Related Work

Robust design is seen by some [29] as a subset of response surface methodology, which in turn is one of the methods employed in the field of Multidisciplinary Design Optimization (MDO), an area of much research for aerospace applications [30]. According to Havakechian [31], a future trend in MDO is to cover not only aerodynamic performance of turbines and compressors, but also geometrical requirements, mechanical integrity and manufacturing costs. Dornberger [32] suggests adding disciplines such as life cycle costs, product life cycle time, weight, emissions and heat transfer to the equation.

Robust design practices have been applied to FEM [33] and CFD [34] , as well as for variation propagation control in aero-engine assembly [35]. In this paper, the connection between these fields of science is investigated in one coupled, multidisciplinary problem.

5 Case study

This section presents a case study that connects geometrical variation in a turbine structure with its functionality, thus investigating the functional robustness of a given turbine structure design.

The purpose of this case study was to find a way to:

1. Validate CAD geometries against the manufactured products.

2. Quantify aleatory geometrical variation.

3. Put geometric variation in a context by comparing its effects to other uncertainties. We looked specifically at computational error associated with physics decoupling and mesh resolution.

5.1 Simulation Platform

In this case study, an integrated simulation platform was used to examine these multidisciplinary criteria. Figure 5 shows the workflow of the platform.

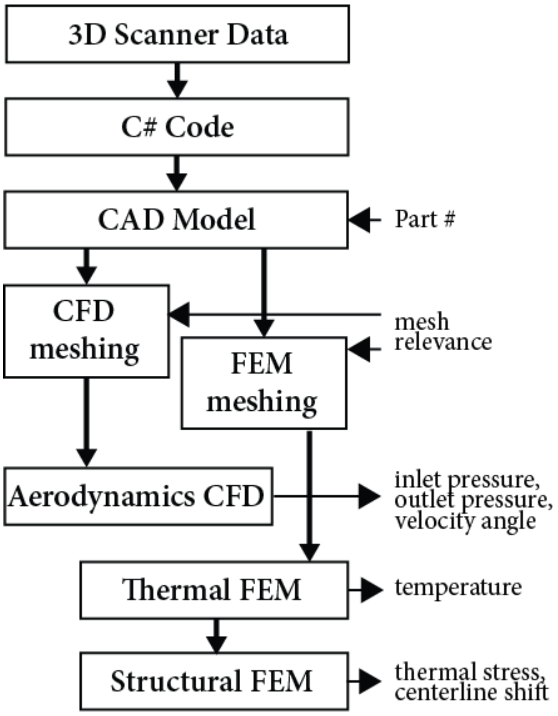


Figure 5: Simulation platform workflow

The platform uses the umbrella software Ansys Workbench, where parameterized CAD models created in NX can be batch-processed through meshing into CFD and FEM analyses. The process is fully automated and follows the traditional workflow for verification of turbine structures.

The turbine structure is shown in Figure 6. The structure is a fabricated assembly, consisting of a number of guide vane T-sections and corresponding hub sections. Two of the T-sections have mount lugs, which are used to attach the aft section of the engine to the aircraft pylon. Ring-shaped flanges are attached to the front and back of the shroud. The parts are placed in fixtures and welded together.

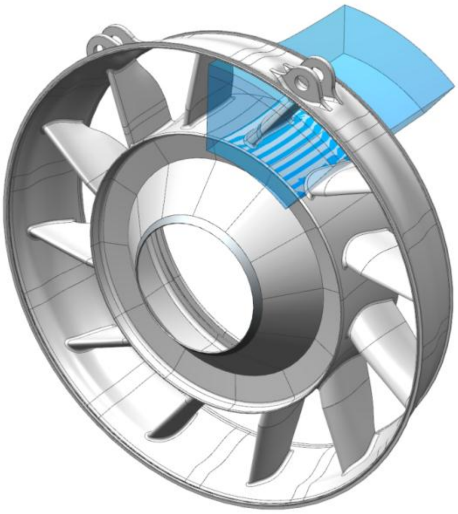


Figure 6: CAD Model - CFD region in blue

In this case study the design space was limited to the assembly of one of the lug T-sections. The T-sections are mounted in fixtures and welded to the assembly.

Three different configurations were evaluated, where the ABC point was moved from the edge towards the center in three steps, as visualized in figure 7. The idea is that by moving this point individually in the fixture for each part, the effect of the geometrical variation in the cast goods could be suppressed in an optimal way.

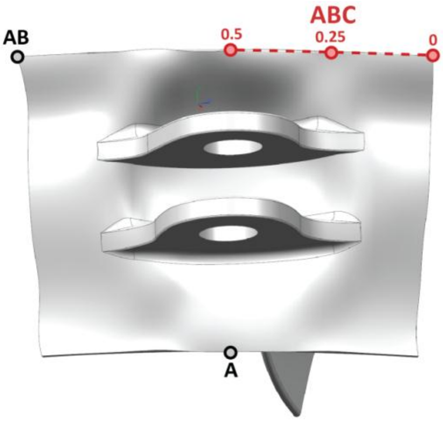


Figure 7: Part Locating Points

5.1.1 Geometry generation

Laser 3D scanning makes it possible to analyze complex geometries on a large scale. Today, 3D scanners typically have measurement ranges around ±5 to ±250 mm, and accuracies at about 1 part in 10,000 and measurement frequency of 40 kHz or higher [36].

Although automated approaches exist that automatically yield CAD parts from scanner data, there are some limitations:

1. 3D scanning only captures non-occluded surfaces, thus only yielding information on a subset of the geometry.

2. The scanned geometry lacks information of abstract concepts of geometrical shape. A CAD model differentiates between spheres, cylinders, rectangles, splines, etc. A laser scanner returns objects as generic shapes defined by a set of data points. A laser-scanned model is not as easily parameterized as a CAD model.

This problem was resolved by mapping the point cloud data to a set of design point parameters. These point parameters corresponded to certain points used in the original CAD generation. In this way, a parameterized CAD model, similar to the original model, could be obtained using the same design practices as in the original model.

The geometry was interpolated from the design point parameters. Spline interpolation [37] was used to create curves from the points. Splines are piecewise-smooth polynomial functions that are commonly used in CAD applications for curve fitting. The splines were second-degree. To interpolate between n points, $(n-2)$ segments were used. This yields an exact solution where the curve touches all points.

The areas between these curves were then swept to generate surface models, which was subsequently uniformly thickened. Separate surfaces were created for the guide vane, the shroud and the mount lugs. The guide vane surface was extended using a support curve so that it fully intersected with the shroud.

As the measurement points were largely focused on the aero side of the surface, the opposing surface was merely the result of the uniform thickening operation. As a final step, the thickened surfaces were trimmed against each other and united into one solid body. All the steps of the process are illustrated in Figure

8. The original design CAD model was used as a reference, as the scanner data can be interpreted in different ways.

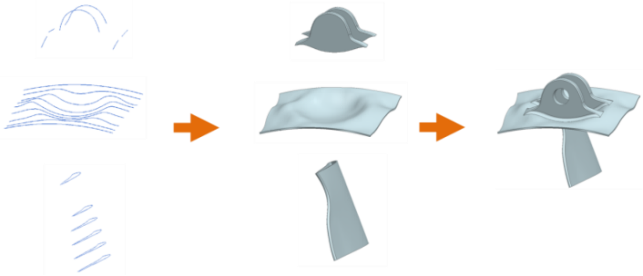


Figure 8: CAD model generation

The model was then virtually assembled, using the 3-2-1 locating scheme defined in Figure 3. Upon this, a virtual welding procedure was performed to connect the mount lugs to the assembly. This welding procedure consisted of sweeping surfaces to create a solid weld between the interfacing parts. Although this procedure is hardly a realistic depiction of the welding process, the final result is nevertheless a fully connected assembly that can be used for applying variation to parts.

Two different CAD geometries were created, one for CFD and one for FEM. The CFD geometry made use of the periodic nature of the aero surface, and modeled only a sectional piece containing one guide vane. The FEM model contained the entire geometry.

5.1.2 *Meshing*

Meshing was done using automated meshing algorithms. Separate meshes were used for the CFD and FEM analysis.

The CFD mesh model used a 30º sectional model with periodic boundary conditions. This significantly reduces simulation time compared to a full 360º degree model. The mesh contained about one million hexahedral cells, with a finer mesh close to the walls. The mesh density was set to ensure sufficient conversion. In the simulation, a realizable K-epsilon model with enhanced wall functions was used.

The FEM mesh was based on the 360º degree model, with roughly one million tetrahedral cells. A nonlinear steady state solver was used.

5.2 Analyses

Three different tests were carried out:

1. Aerodynamics analysis – evaluates the aerodynamic performance of the part. Specifically, the pressure loss over the TRS and the velocity angle at the outlet are calculated. Further, aero surface temperatures are calculated and fed into the subsequent thermal analysis.

2. Thermal analysis – calculates the material temperature from given boundary surface temperatures. The results of the thermal analysis are used to calculate thermal stress.

3. Thermal stress – The recurring thermal loads on the frame create large stresses in the material. This is a limiting factor for product life. Consequently, the thermal stress gives an indication of estimated life. Centerline shift, the movement of the motor shaft centerline because of thermal expansion, was also calculated.

5.2.1 *Simulation times*

The average simulation time for the entire workflow was approximately 90 minutes. The CFD analysis involved approximately 100 iterations. In the simulation, a realizable K-epsilon model with enhanced wall functions was used. As each iteration took a bit less than one minute, the total simulation time for the CFD analysis was around 60-65 minutes.

The six FEM analyses were less computationally intensive than the CFD calculation. The modal analysis took the most time – approximately 20 minutes. The other five analyses took less than 10 minutes.

5.3 Types of uncertainty

The simulation platform can address a broad range of uncertainties. In this section, we evaluate the platform against the comprehensive list of uncertainties in activities conducted in the phases of computational modeling and engineering, put forth by Oberkampf et al. [3]. Figure 9 visualizes the list.

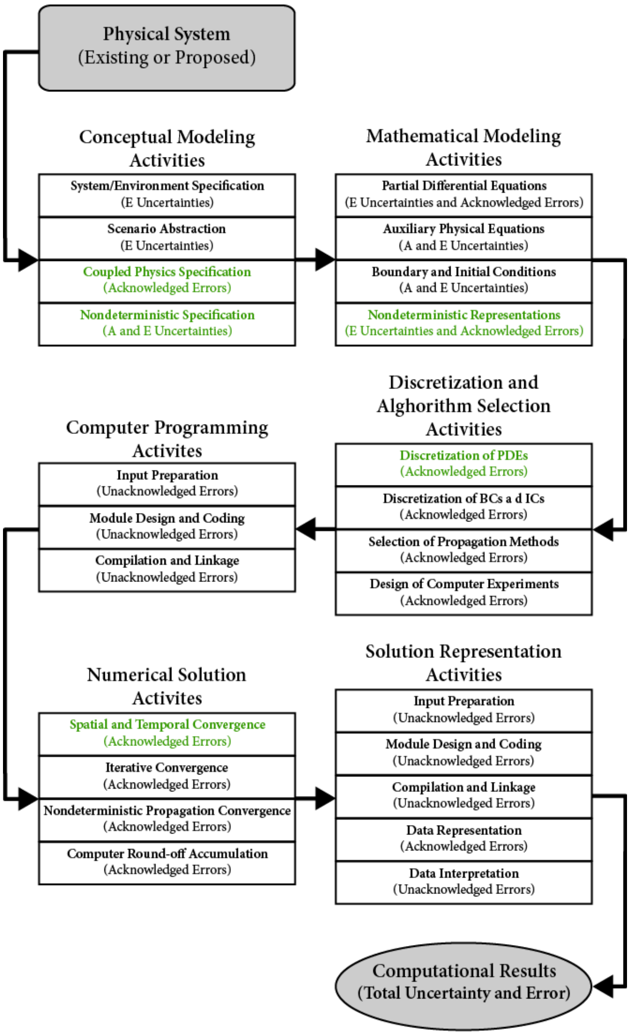


Figure 9: Uncertainties in modeling and simulation.[3] *Text in green shows uncertainties currently addressed in the case study.*

5.3.1 Conceptual modeling activities:

System/Environment Specification: For a subcontractor delivering a subsystem to an OEM, there's a lot of uncertainty in the lack of knowledge of the system and environment. To some extent, this could be addressed as epistemic uncertainties in BCs and ICs, for instance interface loads.

Scenario abstraction: This is a major source of uncertainty. For instance, we only perform static analyses on dynamic phenomena. Dynamic FEM and CFD simulations, however significantly more computationally intensive, could be incorporated in the platform, if only to get an estimate of the error.

Coupled physics specification: In this simulation, a one-way fluid structure interaction is modeled. In this case study, the effects of decoupling CFD and FEM analyses is investigated.

Nondeterministic specification: Aleatory uncertainties in the geometry of the component are the main problem that this paper addresses. However, it would be possible to include variation in material properties, and interface loads.

5.3.2 Mathematical modeling activities

Partial differential equations: This could for instance be the uncertainty in the conservation equations for mass, momentum and energy, which form the basis for our CFD and FEM simulations. These uncertainties are either epistemic or acknowledged errors. They could be addressed in the platform, for instance by changing the CFD method.

Auxiliary physical equations: These are equations that are needed to complete the PDEs. In our case, it could be the turbulence model used in the CFD simulation, or the material-constitutive equations in the FEM. In our platform, an estimate of these types of error can be obtained, for instance by changing from a linear to a nonlinear material model.

Boundary and initial conditions: These uncertainties are straight-forward to account for in the platform. If they are aleatory, a Monte-Carlo sampling of their PDFs would give an estimate of the uncertainty.

Nondeterministic representations: There is an uncertainty associated with assigning a given PDF to a given data sample. In the case of our geometry assurance, the CAD geometries are generated directly from measurement data and no PDFs are needed. However, there is an uncertainty in whether this small sample (20 scans) is representative of reality.

5.3.3 Discretization and algorithm selection activities

A conversion from continuous to discrete mathematics is usually needed to calculate a numerical solution. The solution is thus approximate, and comes with some error. The most apparent discretization is the PDE discretization that is a result of meshing. In the case study, the effect of mesh density is evaluated.

5.3.4 Computer programming activities

Software errors are often an acknowledged source of simulation error. *Input preparation* refers to how the mathematical model is converted into data elements usable by the software. Module design, coding, compilation and linkage refer to the construction of the software itself. In the case study, a combination of commercial software packages and purpose-specific C# code was used. However, the code verification and validation problem (as presented in [18] and [20]) is somewhat difficult to address, and falls out of the scope of this case study.

5.3.5 Numerical solution activities

Numerical solution activates include *spatial, temporal* and *iterative convergence*. In our test case, no transient simulations are performed, and we don't have to worry about temporal convergence. Spatial convergence is somewhat addressed by evaluating mesh density error. Iterative convergence is an inherently part in the Fluent CFD software, and so these effects could be addressed in the platform. However, this falls out of the scope of the case study.

5.3.6 Solution representation activities

The CFD and FEM solutions have millions of data points. This data is then represented by only a handful numerical values; In the CFD solution, the mass-weighted average for inlet and outlet pressure is calculated, and in the FEM, the maximum temperature and deformation. When these values are calculated, some error is inevitably introduced. The bigger problem, however, lies in how to interpret the data. Herein lies the central problem for our case study – knowing that our output variation really is caused by the geometry changes, and not by any of the other listed sources of uncertainty.

6 Results

6.1 Fixture optimization

Figure 10 shows how each output varies as a function of the positioning of the ABC point. The first tree graphs – inlet and outlet pressure, and velocity angle – are results from the CFD calculation. As expected, the inlet pressure doesn't show any significant variation. The outlet pressure, which is a more relevant parameter, shows a variation of in the order of 100 Pascal. The velocity angle also shows some variation.

For the thermal and structural FEM analyses, the most significant variation is in the thermal stress – in some cases, it increases with over 30 percent.

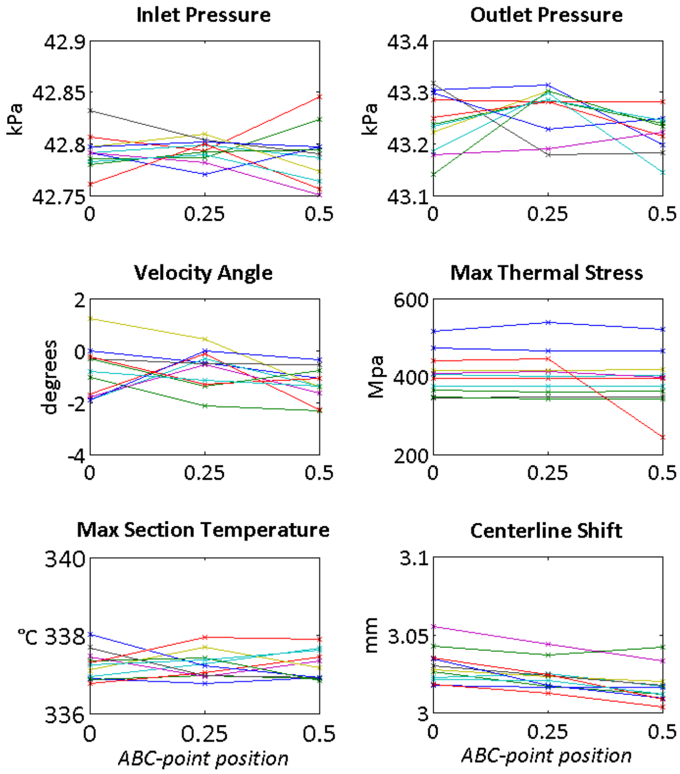


Figure 10: Output as a function of ABC-point position. *Each line represents one scanned part.*

6.2 The effects of mesh density

Figure 11 shows how mesh density affects the outputs. As we can see, these effects are comparable to the effects of geometrical variation.

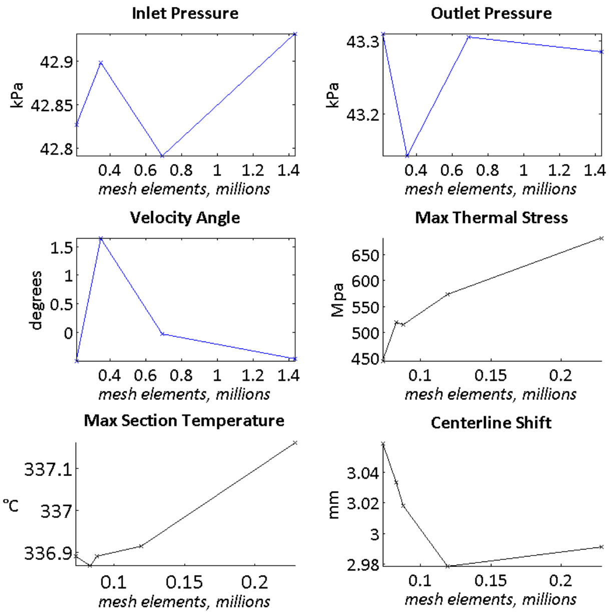
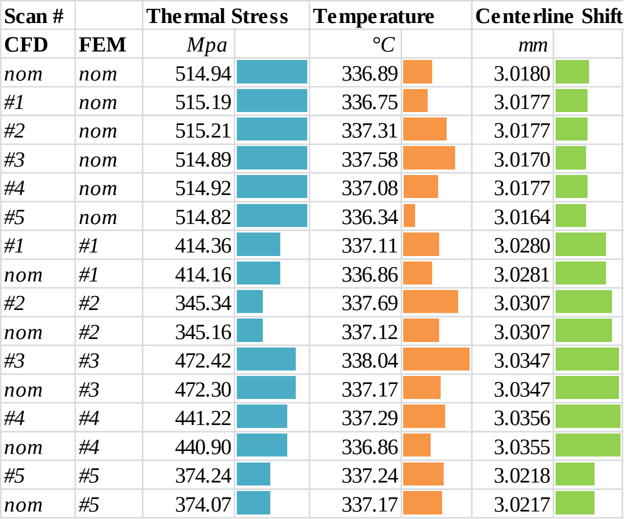


Figure 11: The effects of mesh density

6.3 The effects of decoupled physics

The simulation incorporated a one-way coupling between CFD and FEM simulations – the aero surface temperature provided the boundary condition for calculating material temperature and thermal stress. As mentioned previously, it is straightforward to realize that geometrical variation will affect structural strength. There will be another indirect effect as a change in the aero surface will affect the convective heat flow into the material, resulting in a different thermal expansion and life length. This effect was evaluated switching between boundary values from nominal geometries and scans as inputs for our FEM analysis, as shown in figure 12.

It is apparent that the thermal stress and centerline shift are mostly affected by the geometry change in the FEM phase. The temperature, however, is as affected by the thermal boundary condition, as the variation in structural geometry.



Scan #		**Thermal Stress**	**Temperature**	**Centerline Shift**
CFD	**FEM**	*Mpa*	*°C*	*mm*
nom	*nom*	514.94	336.89	3.0180
#1	*nom*	515.19	336.75	3.0177
#2	*nom*	515.21	337.31	3.0177
#3	*nom*	514.89	337.58	3.0170
#4	*nom*	514.92	337.08	3.0177
#5	*nom*	514.82	336.34	3.0164
#1	*#1*	414.36	337.11	3.0280
nom	*#1*	414.16	336.86	3.0281
#2	*#2*	345.34	337.69	3.0307
nom	*#2*	345.16	337.12	3.0307
#3	*#3*	472.42	338.04	3.0347
nom	*#3*	472.30	337.17	3.0347
#4	*#4*	441.22	337.29	3.0356
nom	*#4*	440.90	336.86	3.0355
#5	*#5*	374.24	337.24	3.0218
nom	*#5*	374.07	337.17	3.0217

Figure 12: The effects of decoupling CFD and FEM analyses

7 Conclusions and discussion

In this case study, we looked how a simulation platform can address aleatory uncertainty in the geometry, and computational error in the meshing and physics decoupling. The simulation platform provides a good tool for investigating the effects of error and uncertainties. However, although the tool has a lot of promise, there is an inescapable dilemma: To investigate the effects of one source of uncertainty, all other sources must be eliminated. As seen in this case study, the effects of geometric variation was partially obscured by meshing error. As a consequence, the quantitative results should be viewed with some skepticism.

However, some of this error could easily be mitigated by increasing mesh density and using a more powerful auto mesher (the meshing capabilities of Ansys Workbench are limited). In order to generate better quality output data, this should be addressed. Nevertheless, this is somewhat beside the point, as the work presented in this paper aimed at provided a method to evaluate geometrical uncertainty, and not any hard data.

The coupling of CFD and FEM analyses are shown to be somewhat superfluous in this test case, as it has a very limited effect on the results. This is good news: As CFD simulations are computationally expensive, a lot of computational time can be saved in structural analysis by using nominal results. However, for multidisciplinary analyses, CFD simulations need to be done anyway to address aerodynamic robustness. Further, creating a coupled system has other advantages. For instance, it makes it easier to respond quickly to a design change in geometry or operating environment.

We believe that addressing uncertainty is central to producing reliable, high-quality products. As noted by Kenny, [17] it is not only is it a tool to improve product quality, but also to enable engineers and decision makers to effectively balance critical project resources against system requirements while accounting for the impact of uncertainty.

Most aerospace companies allocate a lot of resources to manually produce high-quality, high density meshes. Not only is this a costly process in itself, it also adds a lot of computational time in simulation. This is nevertheless a wise decision, as mesh quality is central to obtaining good simulation results. However, failing to account for geometric variation in simulation adds an uncertainty of equal magnitude.

8 Acknowledgements

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Copyright Statement

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