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Manufacturing x Digital

MxD FINAL REPORT PROJECT 15-11-05

Enhancing the Model-Based Definition with Manufacturing Information through Linked Data for Design Exploration

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I. EXECUTIVE SUMMARY

Manufacturing process variability causes product inconsistencies that result in unexpected behavior. Enriching design space exploration with manufacturing process information will enable reduction in overall costs, manufacturing risks, and ensure manufactured products meet system and functional requirements. The objective of this project is to develop a linked data framework to bring manufacturing process information upstream in early product design space exploration, and thus allow for optimization to meet performance, manufacturing and cost requirements.

The purpose of developing a linked data framework with digital web for design space exploration is to provide a seamless digital integration of design to manufacturing stages, to drastically improve performance, productivity and data exchange efficiency.

The following concepts and technologies were developed:

1) An integrated Design Space Exploration (DSE) framework that includes several manufacturing considerations

- Design space representation of manufacturing information using OpenMeta software platform
- Integration of OpenMeta with other modeling and simulation tools such as Siemens NX, GIFT and Siemens Simcenter
- Incorporation of relevant manufacturing processes information, constraints and parameters into DSE
- Generation and inclusion of as-manufactured part model for DSE
- Performance analysis of as-manufactured model

2) A Linked Data Orchestrator (LDO) service that monitors, as generated DSE result sets, transforms DSE-specific data into linked data and automatically persists/populates graph database with result set-driven DSE solutions for future analysis. After the data is uploaded, LDO provides semantic linking of the data on different abstraction level: requirements, as-designed, as-manufactured, functional performance, design space information

3) A web-based Knowledge Portal that provides advanced query, analysis and reporting capabilities on a Linked Data stored in a Graph database(s) from different disciplines and different sources.

The DSE system, LDO service and the Linked Data Knowledge Portal constitute a Linked Data Framework (LDF), that enables linking and sharing information about the design and manufacturing between designers, engineers and other organizations within the network. This widely distributed data exchange targets to increase interoperability and give product designers and manufacturers the ability to evaluate design alternatives, analyze trade-offs, evaluate various ‘ilities’ and conduct risk analyses with seamless information sharing. The end goal is to enable reduction in design turnaround time, manufacturing time to production and product development cycle time, increase in number of viable design solutions and product quality, and reduction in overall cost.

To demonstrate the LDF concept, we utilized an example use case provided by Siemens Energy: a simplified design of a compressor stage bladed rotor disk with a dovetail attachment. Since the fit and surface quality of the blade root and rotor groove play an important role in the capability and operational integrity of the compressor bladed disk assembly, we conducted a design space exploration of the bladed rotor risk with and without accounting for manufacturing variations to demonstrate the added value of “moving manufacturing to the left”. We were able to demonstrate the following:

- Design space exploration integrates the assessment of design requirements and manufacturing capability, both of which are “in the loop” for each design iteration.
- Multiple design options are identified as opposed to single iterations.
- Initial manufacturing parameters for given designs that satisfy profile tolerance requirements are identified.
- Trade off analysis between design requirements, manufacturing capability and cost is enabled for the engineer through LDF
- Quicker design/manufacturing feedback and fewer iterations are possible, thus opening up the potential to significantly reduce new product development time and overall product cost.

II. PROJECT DELIVERABLES

The following list includes all deliverables created through this project. These deliverables will be referenced throughout this report and are accessible on the MxD membership portal in accordance with the rights defined by the Membership Agreement. Specific deliverable include, but are not limited to, the following items.

Table 1: *15-11-05 Project Deliverables*

#	DELIVERABLE NAME	DESCRIPTION	FORMAT OF DELIVERY
1	Final Report	Report on implementation concept, use case, and results	MS Word document Project 15-11-05 Final Report_V1.0.docx
2	Technical Report	Description of software architecture aspects and design decisions for the implementation of the linked data framework for design space exploration	MS Word document Technical_Report_15-11-05.docx
3	Linked Data Management solution to demonstrate Digital Web	Software including following components: a) Linked Data Orchestrator (LDO): service that monitors, as-generated DSE result sets, transforms DSE-specific data into linked data and automatically persists/populates ArangoDB graph database with result set-driven DSE solutions for future analysis. b) Knowledge Portal: provides advanced query, analysis and reporting capabilities on Linked Data stored in graph database. c) User manual and installation guide	Sub-system – LDF Knowledge Portal.zip including: a) DLL b) Python and Java script c) Readme.txt
4	Extended OpeMETA Design Space Exploration (DSE) tool to interface with NX CAD/CAE, GIFT	Design Space Exploration workflow in OpenMETA software including following components: a) Part aligner: assembly alignment prior to FEA b) Solve Finite Element (FE): updates mesh and boundary conditions based on design updates c) Extract FE Results: extract results from Simcenter to OpenMETA workflow d) Expression update: update of parametric CAD model in NX e) GIFT tool: As-manufactured geometry creation module, including user manual and installation guide	Subsystem – Metamorph OpenMETA (with installers).zip including: a) Python journal b) Executable c) Executable d) Executable e) Sub-system - GIFT Tool.zip, Executable and Readme.txt
5	Mating simulation module	Assembly mating module including user manual and installation guide	Sub-system - GIFT Tool.zip including executable and Readme.txt

III. PROJECT REVIEW

Design Space Exploration (DSE) software tools are used extensively in discrete manufacturing industries e.g. automotive, aerospace. Manufacturing process variability can cause product inconsistencies that results in unexpected behavior. Enriching design space exploration with manufacturing process information will enable reduction in overall costs, manufacturing risks, and ensure manufactured products meet manufacturing and functional requirements.

Use Cases & Problem Statement

In today's engineering workflow, design and manufacturing stages are de-coupled. Manufacturing considerations are not fully reflected in Design Space Exploration. Therefore, the communication from design to manufacturing is only one way (**Figure 1**).

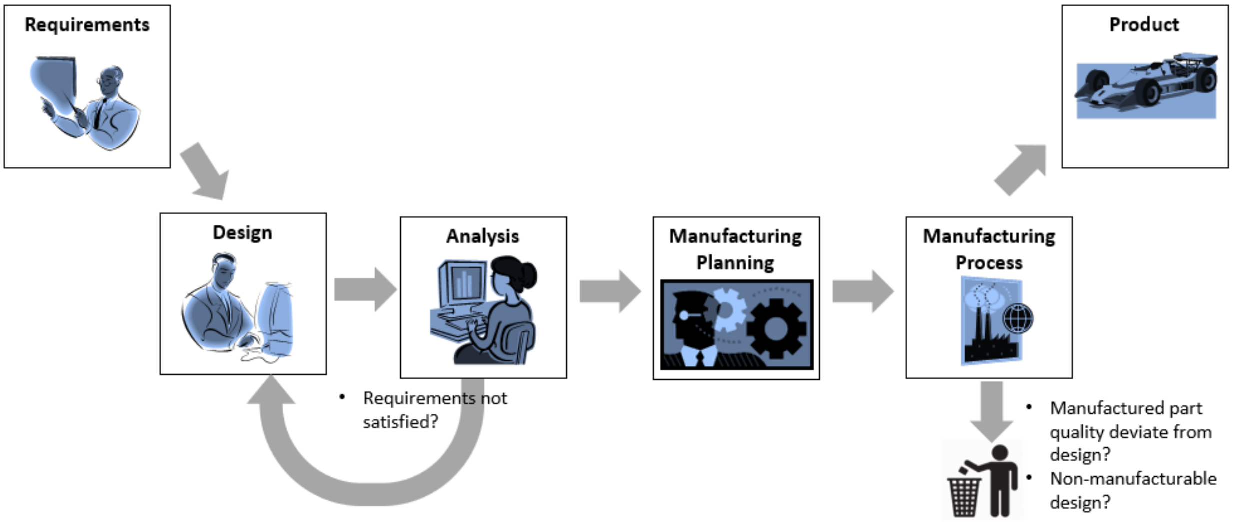


Figure 1: *Engineering workflow*

Since manufacturing considerations are not fully considered in DSE, manufacturing process information are not considered during the design stage (e.g. machine and tool information). Therefore, as-manufactured part may deviate from the as-designed part. Parts often need to be physically produced to identify these defects. This results in increase in cost and design turn-around time. In addition, without considering manufacturing information during design stage, design may be more conservative than it needs to be.

In this project, we aim to address the following use case in the design to manufacturing workflow:

"As a design engineer, I want to incorporate manufacturing process information in early design stages so that I can better optimize product design across performance and manufacturing requirements."

Scope & Objectives

The objective of this project is to develop a linked data framework to bring manufacturing process information upstream in early product DSE (**Figure 2**), and thus allow for optimization to meet performance and manufacturing requirements.

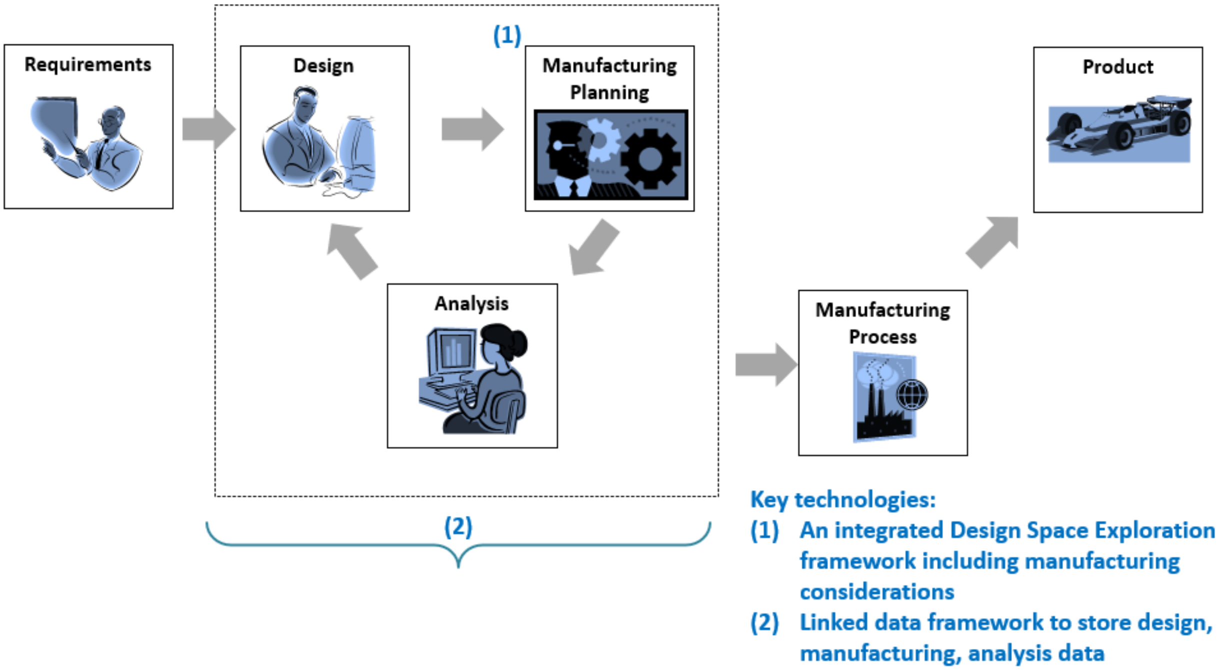


Figure 2: *Moving manufacturing to the left in early design exploration*

The following concepts and technologies have been developed:

1) An integrated DSE framework that includes manufacturing considerations

- Design space representation of manufacturing information
- Incorporation of relevant manufacturing processes information, constraints and parameters in DSE
- Generation and inclusion of as-manufactured part model for DSE
- Performance analysis of as-manufactured model

2) A linked data framework that enables the user to query data from different disciplines e.g. design, manufacturing, analysis

- Semantic web to store design, manufacturing and design space exploration data
- Linked data based approach
    - Web-based resources: as-designed, as-manufactured, design performance data
    - Semantic link between resources

Planned Benefits

This project aims at extending model-based definition to include manufacturing information through a linked data that presents the following key innovations:

- “Move manufacturing to the left”: Incorporate manufacturability and functional analysis during early design stage
- Data traceability via digital web: Queries on semantic links between design, manufacturing and analysis data in the digital web

In the linked data framework, as-manufactured model and process information are embedded in design space exploration workflow. It enables seamless design and manufacturing information linkage. Leveraging the linked data framework for design and manufacturing space exploration, it is expected to introduce the following benefits to the end user’s design to manufacturing workflow:

- Improvement in as-manufactured part quality and cost
  - Extended design space: Manufacturing processes information parameters become part of design variables
  - Increase in number of viable design solutions
  - Inclusion of as-manufactured CAD model to better predict product performance
- Increase in productivity
  - Seamless workflow from design to manufacturing analysis
  - Reduction in out of phase work, design turnaround and product development cycle time
  - Reduction in manufacturing time to production
- Linked data traceability
  - Easy query of design, manufacturing and analysis data

IV. TECHNICAL APPROACH

Manufacturing process variability causes product inconsistencies that result in unexpected behavior. Enriching design space exploration with manufacturing process information will enable reduction in overall costs, manufacturing risks, and ensure manufactured products meet system and functional requirements. The objective of this project is to develop a linked data framework to bring manufacturing process information upstream in early product design space exploration, and thus allow for optimization to meet performance, manufacturing and cost requirements.

The purpose of developing a linked data framework with digital web for design space exploration is to provide a seamless digital integration of design to manufacturing stages, to drastically improve performance, productivity and data exchange efficiency.

The following concepts and technologies were developed:

1) An integrated Design Space Exploration (DSE) framework that includes several manufacturing considerations

- Design space representation of manufacturing information using OpenMeta software platform

- Integration of OpenMeta with other modeling and simulation tools such as Siemens NX and Simcenter, and Georgia Tech's GIFT tool.
- Incorporation of relevant manufacturing processes information, constraints and parameters into DSE
- Generation and inclusion of as-manufactured part model for DSE
- Performance analysis of as-manufactured model

2) A Linked Data Orchestrator (LDO) service that monitors, as generated DSE result sets, transforms DSE-specific data into linked data and automatically persists/populates graph database with result set-driven DSE solutions for future analysis. After the data is uploaded, LDO provides semantic linking of the data on different abstraction level: requirements, as-designed, as-manufactured, functional performance, design space information

3) A web-based Knowledge Portal that provides advanced query, analysis and reporting capabilities on a Linked Data stored in a Graph database(s) from different disciplines and different sources.

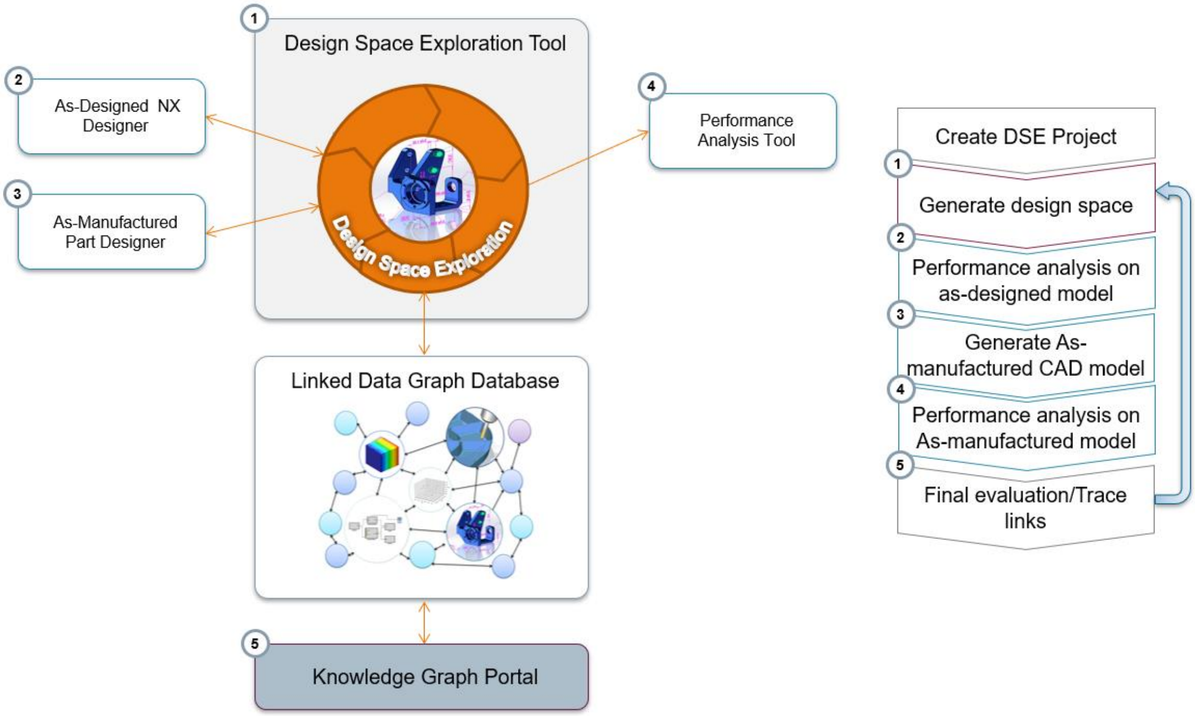


***Figure 3**: Conceptual view of the Linked Data Framework for Design Space Exploration*

The DSE system, LDO service and the Linked Data Knowledge Portal constitute a Linked Data Framework (LDF), that enables linking and sharing information design and manufacturing information between designers, engineers and other organizations within the network. This widely distributed data exchange targets to increase interoperability and give product designers and manufacturers the ability to evaluate design alternatives, analyze trade-offs, evaluate various 'ilities' and conduct risk analyses with seamless information sharing. The end goal is to enable reduction in design turnaround time, manufacturing time to production and product development cycle time, increase in number of viable design solutions and product quality, and reduction in overall cost. **Figure 3** depicts the concept of the LDF for the design space exploration.

System Architecture

The high-level architecture that is summarized in **Figure 4** depicts a set of core subsystems that comprises the overall Linked Data Framework (LDF) and is described in details in the Technical Report (1). The given architecture supports but is not limited to two logical tiers: Client Tier (Knowledge Portal, DSE Client) and Digital Thread Tier (LDO, GraphDb, Data Store (files, server etc.). Depending on the deployment specifics, that can vary by different organizations LDO, GraphDb and the Data Store could potentially be deployed on different enterprise nodes.

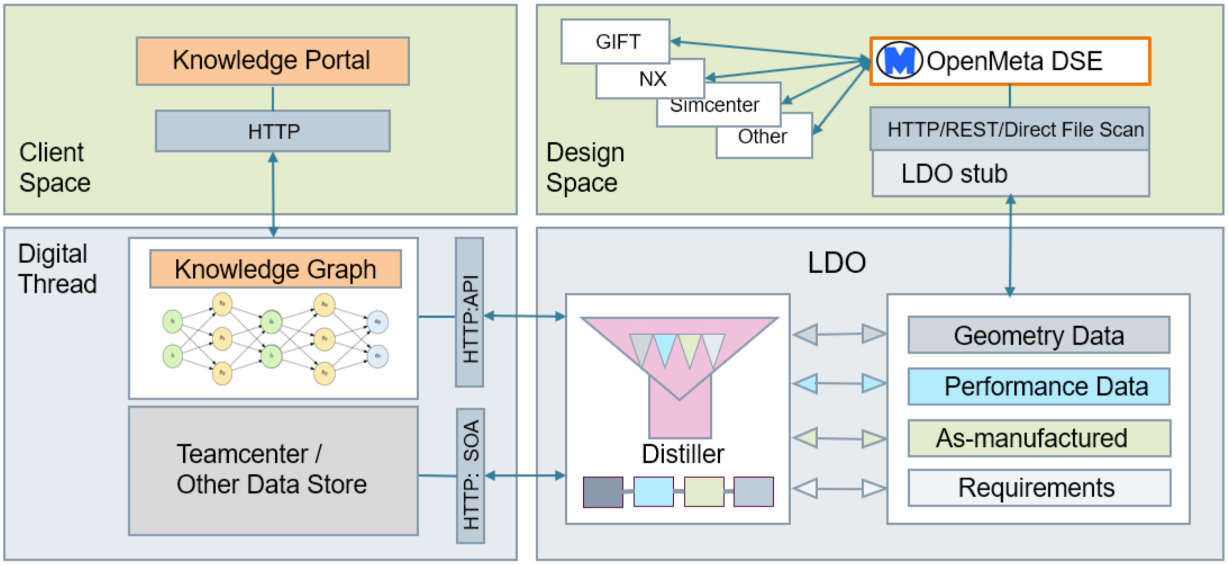


Figure 4: Architecture overview

The Client Space tier consists of a computational node that is deployed on enterprise network and hosts Knowledge Portal for DSE solutions query, analysis and reporting. The Knowledge Portal is implemented using latest web technologies such as NodeJS, Java Script and HTML5-style UI elements for data query, analysis, synthesis and reporting

Design Space:

The Design Space tier consists of a computational node that is deployed on enterprise network and hosts the OpenMeta platform to design and run DSE experiments. In addition, all auxiliary modeling and simulation tools integrated with OpenMeta, such as GIFT, NX and Simcenter are considered as part but not limited to a Design Space tier.

Digital Thread:

The Digital Thread tier consists of one or more computational nodes that host persistent storage (GraphDb or enterprise persistency solution, such as Teamcenter, file store server etc.) In this demonstration Arango DB is used to store DSE result sets in a form of a graph. Arango DB provides Client-Side API for data exchange and AQL for data query. Both technologies are utilized/implemented by LDO. The LDO-Arango component is implemented in Python. It integrates HTTP protocol for communication with Arango DB via Arango Client SOA API. LDO establishes connection with Arango DB on LDO startup and responsible for maintaining connection through its runtime session. Arango provides AQL for the graph data query. AQL is a declarative query language letting you access the very same data with a broad range of access patterns like traversals, JOINs, search, geospatial or any combination.

Linked Data Orchestrator (LDO):

The Linked Data Orchestrator is a software executable component that is responsible for parsing (distilling) DSE results from the OpenMeta. Its scans DSE results directory every 30 seconds (configurable). It parses OpenMeta json-formatted result files int its distiller environment. As soon as new results are parsed, LDO constructs an ontological model of the DSE result sets, semantically linking data and parsing the entire model in a form of Arango Graph into Arango DB. This operation runs as continuous runtime loop that can be disrupted or ended by the LDO user/administrator.

Design Space Exploration workflow in OpenMETA

For this effort, a design space exploration was created to explore the design space in terms of parametric variations possible and their effects on the system’s KPI. In addition, the effects of manufacturing decisions were also brought forward in the design process as manufacturing parameters that are also included in the design space to be explored.

The OpenMETA tools were used to implement the DSE for this effort. The OpenMETA framework is an integrated, open source, model-based platform used to design and analyze complex systems and is very well adapted to handle very large design spaces. It is comprised of a modeling environment, a test execution framework, and a results management and visualization system.

A core component of OpenMETA is the design space exploration tool (DESERT). DESERT encodes architecture choices, discrete component alternatives, and parametric variations for the entire system design. More specifically, DESERT support parametric design space exploration through the Parametric Exploration Tool (PET). This tool facilitates design space exploration using parameter optimization techniques and supports a design of experiments approach.

A Parametric Exploration model contains a Test Bench, which has inputs (i.e., parameters) and outputs (i.e., metrics), and a parametric exploration driver object, which can be an optimizer, a parameter study (i.e., design of experiments). The PET tool generates an executable experiment from the Parametric Exploration model, consisting of generating executable models for Test Bench in the Parametric Exploration model. Among the supported Test Benches are tightly integrated tooling such as CAD Assembly Test Benches and also loosely integrated tooling such as FEA solvers, custom developed manufacturing analysis tooling, etc.

Figure 5 shows the Parametric Exploration model in OpenMETA used to implement the DSE for this effort. On the left, a Parameter Study Driver drives in user-specified Design Variables for both design and manufacturing parameters for the study. Objectives are specified to capture computed Metrics representing KPI's of the design study and may also include secondary/intermediate values to be recorded as part of the analysis.

The PET executes the DSE for a number of iterations specified by the user. At each interaction the Parameter Study Driver selects the value of the Design Variables according to the user-specified sampling method, such as Uniform sampling or Latin Hypercube sampling method. The uniform sampling method was used in this effort and selects parameters according to a uniform distribution across the ranges (or static values) specified for each variable.

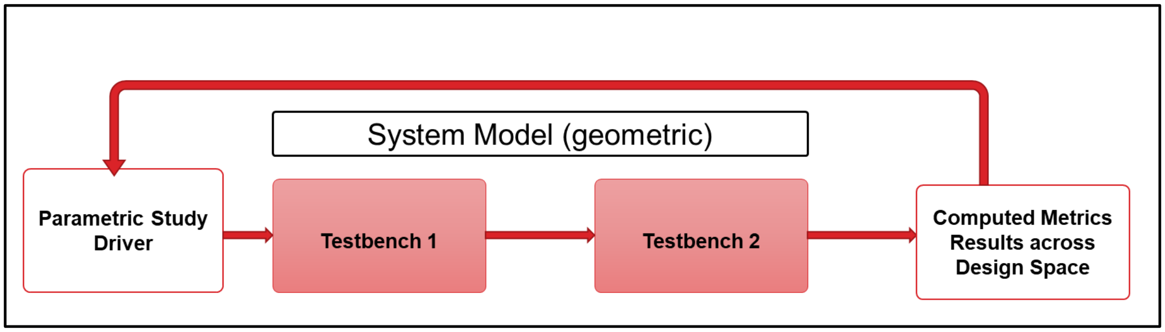


Figure 5: *Figure: DSE Implementation in OpenMETA (as a Parametric Exploration Tool)*

Two Test Benches were created to integrate the model-based analyses used in this effort.

Test Bench 1 was created to facilitate the execution of the As-Manufactured simulation used to calculate the effects of manufacturing-induced form errors. These errors computed will be used to parameterize the CAD part geometry to represent the predicted as-manufactured geometry (see next section for a detailed description).

Test Bench 2 was created to run the Stress Analysis and compute the KPI's for the design.

Generation of as-manufactured surfaces

The purpose of the as-manufactured surface generation module is to generate the as-manufactured geometry with known manufacturing-induced form errors, given the as-designed CAD model of a product and the associated manufacturing process and its parameters. **Figure 6** schematically depicts this concept.

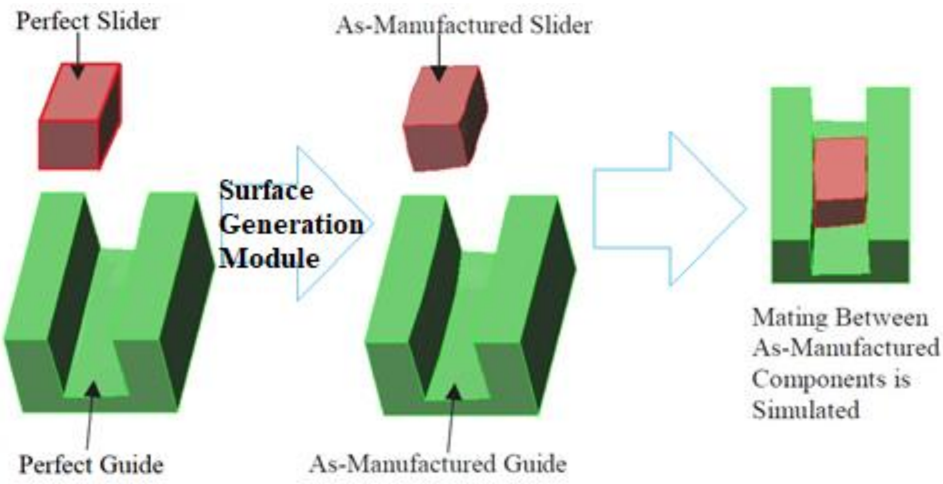


Figure 6: *Illustration of the as-manufactured surface generation concept.*

In this project, a machining process – peripheral end milling – was considered as an example of a manufacturing process that induces form errors. Specifically, cutting forces produced by the peripheral end milling process cause the cantilevered tool to instantaneously deflect and thereby introduce form errors on the machined surface. These errors cause the machined surface geometry to deviate from the nominal CAD geometry. In practice, additional sources of machining-induced error such as machine tool axes errors, tool wear, etc. exist but these are not considered in this project. However, the methodology utilized in this project to incorporate manufacturing-induced errors into a CAD model is generic and can be extended to include other manufacturing process-induced geometric errors that can influence the functional behavior of the part surface.

As noted above, the as-manufactured surface generation module developed in this project consists of a mechanistic model of the nominal milling forces and cutter deflections produced in the peripheral milling process. The underlying models are well-documented in the scientific literature (see (2) (3) (4)) and have been extensively validated through experiments by a multitude of authors. The specific models for cutting force prediction and for simulating the surface error in this project were derived from the work of Kline et al. (2) (3).

Since the use case considered in the project consisted of a gas turbine rotor disk and individual rotor blades assembled into complex shaped grooves machined into the disk, the functionally critical surfaces of interest were limited to the inclined pressure faces in the machined grooves. Simulating the as-manufactured form error produced in peripheral milling of the inclined pressure faces required modification of the mechanistic force model presented in Kline et al. (2) (3) to account for the form milling cutter utilized to mill the pressure faces. **Figure 7** shows an example of such a form cutter where the cutting edges participating in the cutting action are on the tapered portion of the cutter.

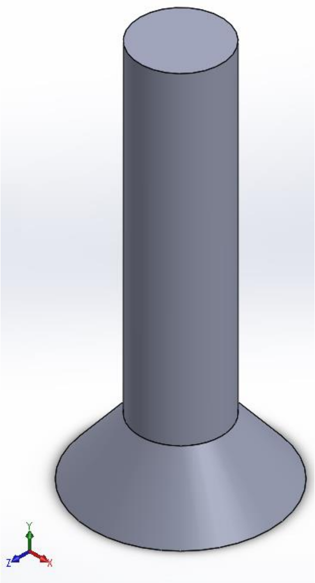


Figure 7: *Nominal shape of the form cutter modeled in the project.*

The inputs to the as-manufactured surface generation software module and their units (wherever applicable) are as follows:

1. Number of flutes in the milling tool
2. Feed per tooth [mm per tooth]
3. Tool diameter [mm]
4. Tool length [mm]
5. Helix angle on the tool [degree]
6. Modulus of elasticity of the tool material [MPa]
7. Length of dovetail [mm]
8. Inclination angle of the pressure faces in the groove [degree]
9. Radial depth of cut [mm]

The output of the as-manufactured surface generation module consists of the 2-D as-manufactured surface profile as a function of the axial depth of cut. For simplicity, the as-manufactured surface profile is approximated as a straight line connecting the as-manufactured profile at the top and bottom of cut. This essentially boils down to altering the as-designed inclination of the pressure faces in the disk groove. The left figure in **Figure 8** shows an example of the simulated as-manufactured surface where the blue curve shows the simulated as-manufactured surface profile due to cutter deflection while the red line shows the straight line approximation of the as-manufactured surface profile. Note that the scales of the horizontal and vertical axes are not identical in order to illustrate the as-manufactured surface error. The as-manufactured surface is then generated as a swept surface of the approximated as-manufactured profile along the path of milling tool movement. The right figure in **Figure 8** shows the as-manufactured surface generated from the approximated as-manufactured profile shown to its left.

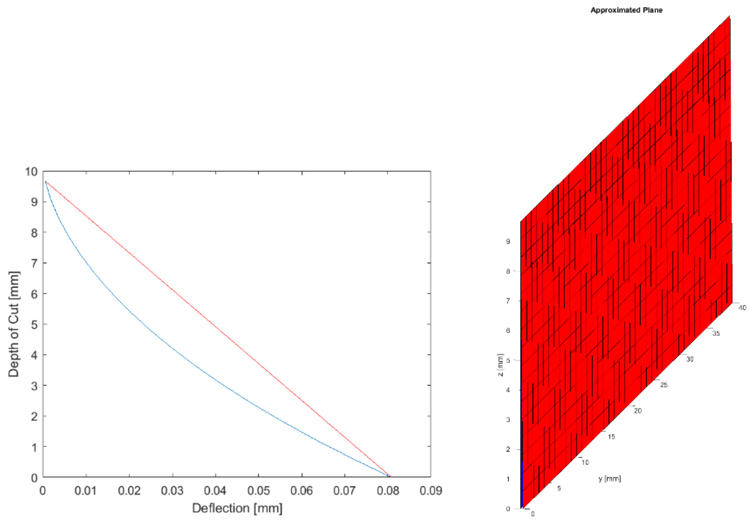


Figure 8: *Left: Example of as-manufactured surface profile; Right: Example of as-manufactured surface (in-red) (notice the small inclination of the surface at the bottom).*

Since it is difficult to analytically model the deflection of a specific form cutter and generate the corresponding as-manufactured surface profile, the form cutter was approximated as a cylindrical milling cutter of equivalent tool diameter that produces the same load-deflection characteristics as the form cutter. To calculate the equivalent cylindrical tool diameter, the form cutter with its exact geometry was modeled in a finite element software (ANSYS Student 2019 R3) and the deflection of the cutter when a distributed load was applied to the tapered portion of the form cutter was simulated. **Figure 9** shows an example result obtained from a typical finite element run.

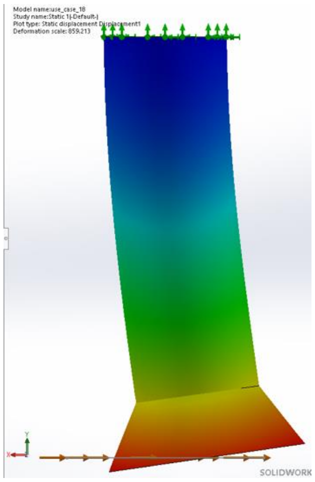


Figure 9: *Example form cutter deflection obtained from finite element analysis.*

After the form cutter deflection profile was generated using finite element analysis, the maximum deflection at the bottom of the form cutter was recorded. To calculate the equivalent cylindrical tool diameter it was assumed that, for a given force, the equivalent cylindrical cutter produces the same maximum deflection as the form cutter. For a cylindrical cutter, the maximum deflection at the bottom of the tool can be calculated using Equation 1:

$$\delta_{max} = \frac{FL^3}{3EI}, I = \frac{\pi r^4}{4}$$

Equation 1

where δ_{max} is the maximum deflection at the bottom of the cutter, *F* is the point force applied at the bottom of the cutter, *L* is the length of the tool, *E* is the Modulus of Elasticity of the tool material, *I* is the moment of inertia of the cross-section of the cylindrical cutter, and *r* is the diameter of the cylindrical cutter. Thus, given *L*, *E*, and the form cutter geometry, and δ_{max} under load *F*, the equivalent cylindrical tool diameter $D_{equivalent}$ can be calculated using Equation 2:

$$D_{equivalent} = 2 * (\frac{FL^3}{3E\delta_{max}} * \frac{4}{\pi})^{\frac{1}{4}}$$

Equation 2

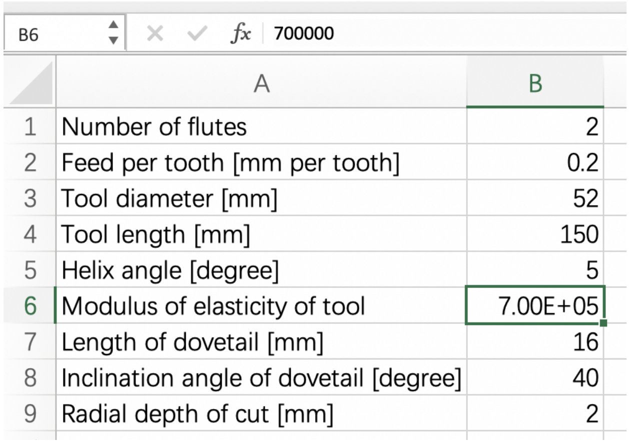
After obtaining the equivalent cylindrical cutter diameter, it was discretized into slices along the axial depth of cut as described in (2), and the deflection of each slice due to the force acting normal to the machined surface at the point of surface generation was computed to generate the as-manufactured surface profile.

The basic algorithm of the as-manufactured surface generation module can be summarized as follows:

1. Compute the cutting forces produced by the form cutter in one revolution of the cutter as it translates in the feed direction
    - At each angular position during cutter rotation, the elemental forces in the X and Y directions produced by the cutting edges engaged with the workpiece in each slice along the Z axis (tool axis direction) are computed and summed to obtain the total instantaneous X and Y forces acting on the tool (X direction is the tool feed direction; Y direction is normal of the machined surface). This is repeated for all axial slices and angular positions of cutter rotation over one cutter revolution. See (2) for details.
2. Determine the equivalent diameter of a cylindrical cutter that produces the same load-deflection response as the actual form cutter. This is accomplished using the finite element analysis procedure discussed above.
3. Using the equivalent cylindrical cutter, compute the force centers at each angular position the cutter as described in (3).
4. Compute the static deflection of the equivalent cylindrical cutter along the axial depth of cut at the surface generation points for each angular position of the cutter (see (3) for details).

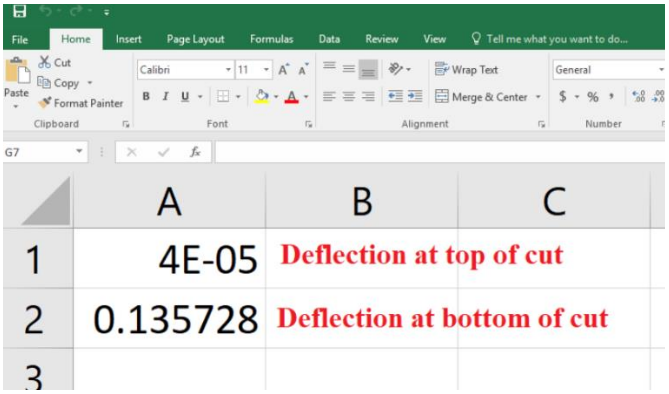
5. Generate the as-manufactured surface profile by approximating the deflection of the equivalent cylindrical cutter as a straight line that connects the deflection at the top and bottom of the cut.

The as-manufactured surface generation module was coded in C#. The code intakes an Excel file that contains the manufacturing process parameters and generates an Excel output file that contains the as-manufactured deviations (in mm) at the top and bottom of the axial depth of cut. **Figure 10** shows an example of the input Excel file while **Figure 11** shows an example of the output Excel file.



	A	B
1	Number of flutes	2
2	Feed per tooth [mm per tooth]	0.2
3	Tool diameter [mm]	52
4	Tool length [mm]	150
5	Helix angle [degree]	5
6	Modulus of elasticity of tool	7.00E+05
7	Length of dovetail [mm]	16
8	Inclination angle of dovetail [degree]	40
9	Radial depth of cut [mm]	2

Figure 10: *Screenshot of a sample input Excel file.*



	A	B	C
1	4E-05	Deflection at top of cut	
2	0.135728	Deflection at bottom of cut	
3			

Figure 11: *Screenshot of a sample output Excel file.*

Mating simulation

The purpose of the mating simulation is to predict the final position and orientation of the as-manufactured part when it is mated with a corresponding as-manufacturing part (e.g., during assembly). **Figure 12** depicts this for an example slider-guideway assembly scenario where the as-manufactured model of the slider is to be mated with an as-manufactured model of a guideway. The objective is to find the final mated position and orientation of the as-manufactured slider in the guideway.

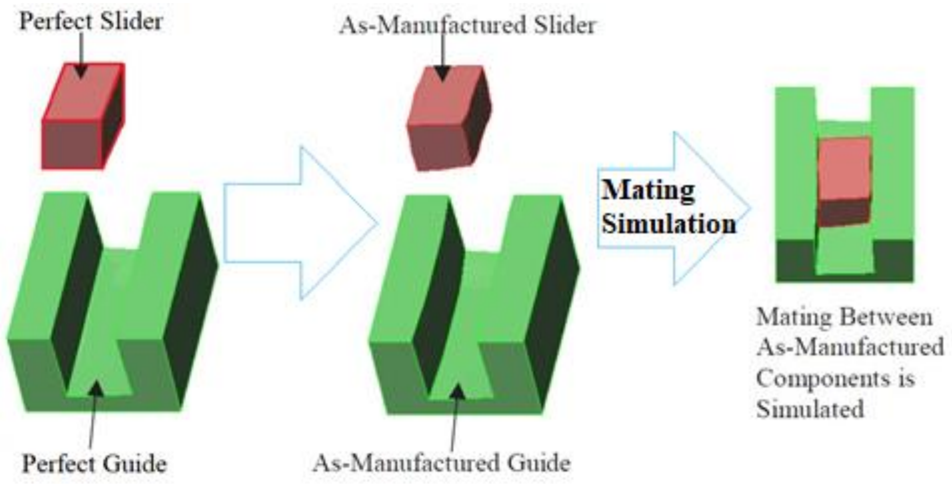


Figure 12: *Illustration of the purpose of the mating simulation module*

The mating simulation considers the assembly of two parts. The simulation assumes that one of the parts ("stationary part") is fixed while the other part ("mating part") needs to change its position and orientation in order to "mate to" the stationary part to fit the given assembly requirements. For example, in **Figure 12**, the green as-manufactured guide is the stationary part and the red as-manufactured slider is the mating part. During the mating simulation, the slider adjusts its position and orientation to enable assembly into the guide. If the assembly involves more than two parts, the mating simulation needs to be performed sequentially.

In this project, the mating simulation module was used to calculate the deviations in position and orientation of the as-manufactured mating part with the as-manufactured stationary part.

The inputs required for the mating simulation module are as follows:

1) The mating relationships between surfaces of the mating and stationary parts. This consists of the identifiers of surfaces of the mating and the stationary parts that need to be mated with each other during assembly. Irrespective of the part concerned, a surface involved in a mating relationship is termed a "mating surface" whereas a surface with no mating relationship is termed a "non-mating" surface.
2) For each surface of the mating part (represented by a grid of points called "surface points"):
    i. Point coordinates of the surface points, P_{Fij}
    ii. Point normal at each surface point, n_{Fij}
    iii. Surface label: either as a mating or a non-mating surface
3) For each surface of the stationary part (also represented by a grid of points called "surface points"):
    i. Point coordinates of the surface points, s_{Fij}

ii. Surface label: either as a mating or a non-mating surface

The algorithm for the mating simulation module is taken from Scott Pierce's work (5). The overall algorithm for the mating simulation can be regarded as an optimization algorithm that seeks to minimize the following objective function:

$$Minimize: Z(roll, pitch, yaw, x, y, z) = [(\frac{1}{\sum_{F=1}^{N} m_F n_F})(\sum_{F=1}^{N}\sum_{i=1}^{m_F}\sum_{j=1}^{n_F}((W_F d_{ij}(\vec{x})^{non-interfering})^2 + (W_{INT} d_{ij}(\vec{x})^{interfering})^2))]^{\frac{1}{2}} \quad \text{(Equation 1)}$$

where N is number of surfaces of the mating part; m_F is the number of rows of surface points of the F^{th} surface of the mating part (Note: each surface of the mating part is represented by a grid of surface points); n_F is the number of columns of surface points of the F^{th} surface of the mating part; i and j denote the surface point in the i^{th} row and j^{th} column of the F^{th} surface of the mating part (denoted as p_{Fij}); $d_{ij}(x)^{non-interfering}$ denotes a) the smallest distance between the surface point p_{Fij} of the F^{th} surface of the mating part and the stationary part, and b) the mating part at point p_{Fij} does not interfere with the stationary part; W_F is a weight that is 1 if the F^{th} surface containing p_{Fij} has a mating relationship and is 0 otherwise; $d_{ij}(x)^{interfering}$ denotes a) the smallest distance between surface point p_{Fij} in the F^{th} surface of the mating part and the stationary part, and b) the mating part at point p_{Fij} does interfere with the stationary part; W_{INT} is a penalty weight that has a value of 100; *roll*, *pitch*, *yaw*, x, y, z represent the orientation and position of the mating part.

The physical interpretation of Equation 1 is as follows:

> *Adjust the orientation and position of the mating part to minimize the total distance between the surface pairs that have mating relationships while keeping the mating part and stationary part separate so as not to interfere with each other*.

To check if the aforementioned surface point p_{Fij} interferes with the stationary part, the surface normal at point p_{Fij}, n_{Fij}, is utilized. **Figure 13** illustrates the method for interference checking.

As shown in **Figure 13**, *Mating Surface* denotes a surface on the mating part where p_{Fij} is located. s_{Fij} denotes the corresponding point on the stationary part that has the smallest distance to p_{Fij}. *Stationary Surface* denotes the surface on the stationary part where s_{Fij} is located. n_{Fij} denotes the surface normal of the Mating Surface at point p_{Fij}. $d_{ij}(x)$ in Equation 1 is defined as the norm of the vector (s_{Fij} - p_{Fij}). The rule for interference checking is defined as follows:

> *If the dot product of vector n_{Fij} and (s_{Fij} - p_{Fij}) is equal or larger than 0, then the mating part at point p_{Fij} does not interfere with the stationary part. Otherwise, the mating part at point p_{Fij} interferes with the stationary part.*

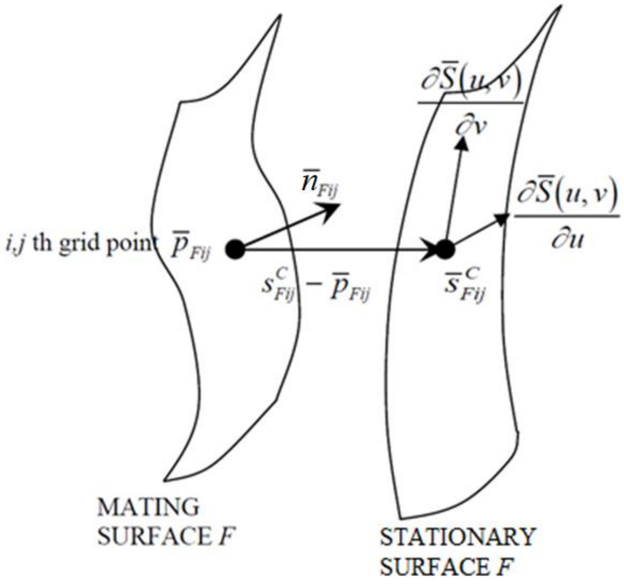


Figure 13: *Method for interference checking*

Note that in the mating simulation module implementation, the stationary surfaces are first parametrized by a series of polynomials of Order 3, and then s_{Fij} is found by minimizing $d_{ij}(x)$ using the simulated annealing algorithm. Since this process is extremely time-consuming (especially when combined with the Hook-Jeeves algorithm used to minimize the overall objective function), an approximation can be applied to reduce the computation time. Specifically, instead of parametrizing the stationary surface and finding the precise location of s_{Fij}, since the stationary surface is also input as a number of surface points, the location of s_{Fij} can be approximated as the location of the surface point that has the smallest $d_{ij}(x)$ among all the surface points in that stationary surface. One limitation of this approximation is that the stationary surface must be a planar surface. Otherwise this approximation can cause errors in interference detection.

Figure 14 shows a schematic of the algorithm used in the mating simulation module. As shown in **Figure 14**, the mating simulation module utilizes the Hook-Jeeves algorithm to find the orientation and position of the mating part that corresponds to minima of the objective function. To find the position and orientation that corresponds to a global minimum, a random-move after finding the local minima needs to be performed. The basic idea for the random move is that once the search point arrives at the local minima, it is moved in a random direction to an unsearched area and the Hook-Jeeves algorithm is utilized again to search for a local minima starting at the new location. The random move keeps restarting the Hook-Jeeves algorithm until the maximum number of iterations is reached. Details of the random search algorithm can be found in (5). Note that since the overall objective is multivariate, non-linear, and discontinuous in the hyperspace, the mating simulation module can take up to 3 hours to run for a single trial (with stationary surfaces parametrized). Even with approximation of not parametrizing the stationary surface, the algorithm still takes up to 15 minutes to run for a single trial.

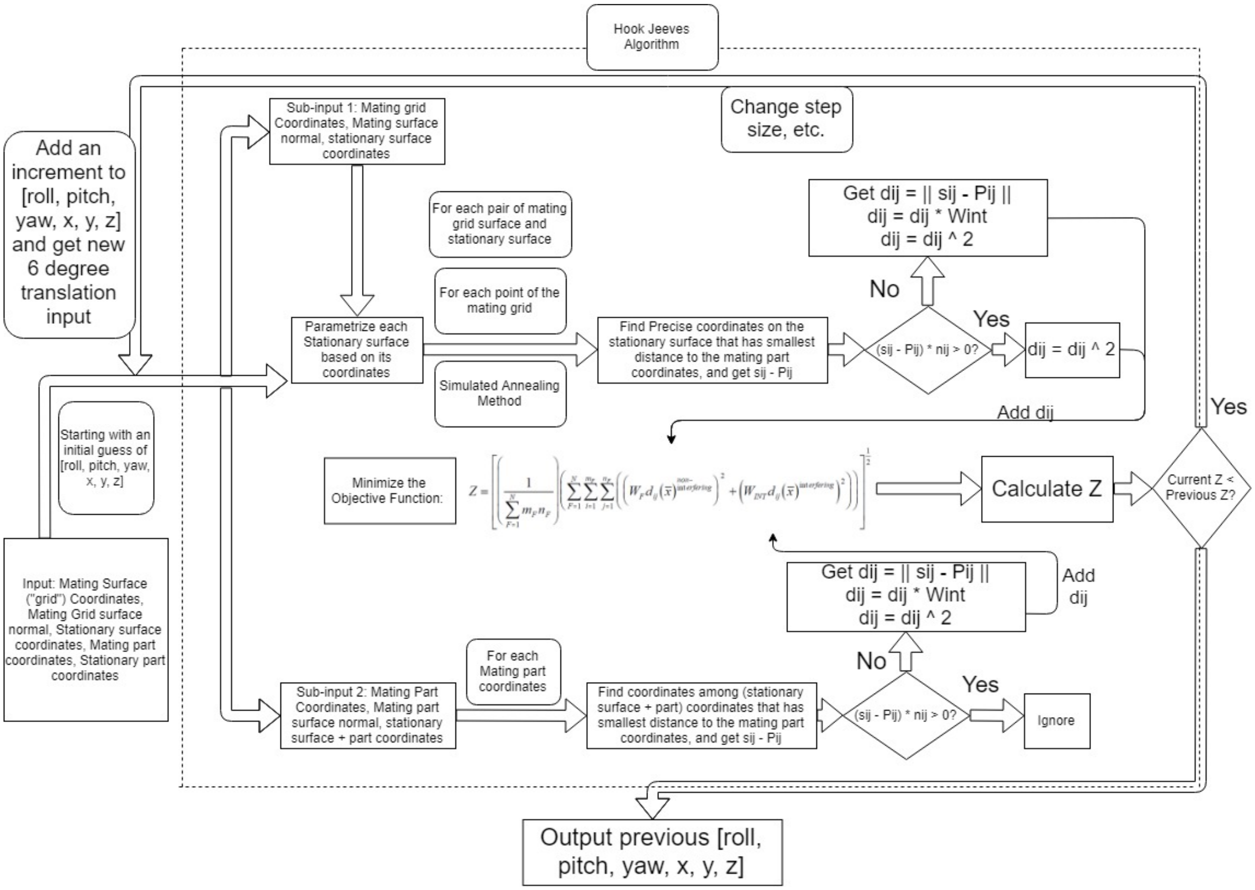


***Figure 14**: Schematic of the algorithm used in the mating simulation module*

Figure 15 shows some examples of the mating simulation. The mating part is represented by a simplified blade root (blue face in the figure), and the stationary part is represented by the simplified groove. **Table 2** shows the results of these mating simulations.

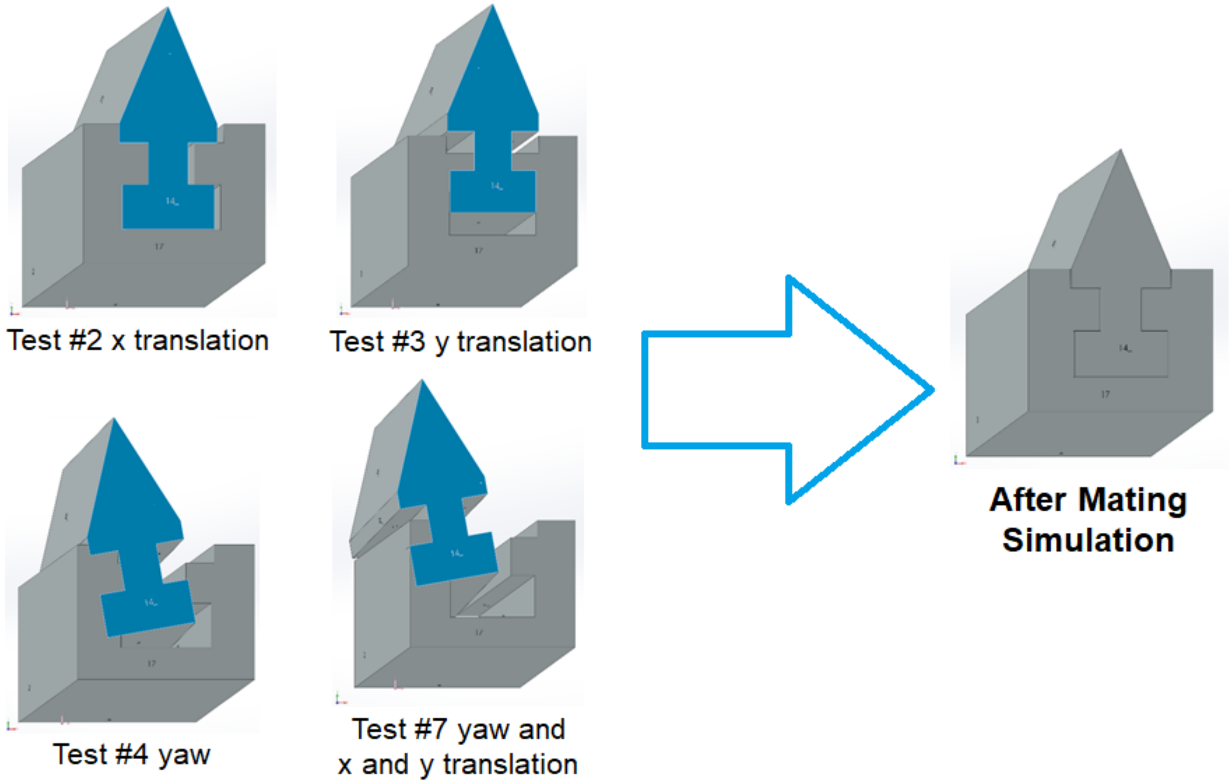


Figure 15: *Examples of mating simulation applied to the simplified blade root and groove features.*

Table 2: *Results of mating simulation examples.*

Test#	#Purpose of test	Success?	Duration[sec]
1	Original Calibration	Yes	300.23
2	Varying x translation with 0.1 accuracy	Yes	403.54
3	Varying y translation with 0.1 accuracy	Yes	303.98
4	Varying yaw (rotation about z-axis) with 0.1 accuracy	Yes	803.79
5	Varying x and y translation with 0.1 accuracy	Yes	353.45
6	Varying yaw and x translation with 0.1 accuracy	Yes	578.64
7	Varying yaw, x, and y translation with 0.1 accuracy	Yes	900.26

Part aligner

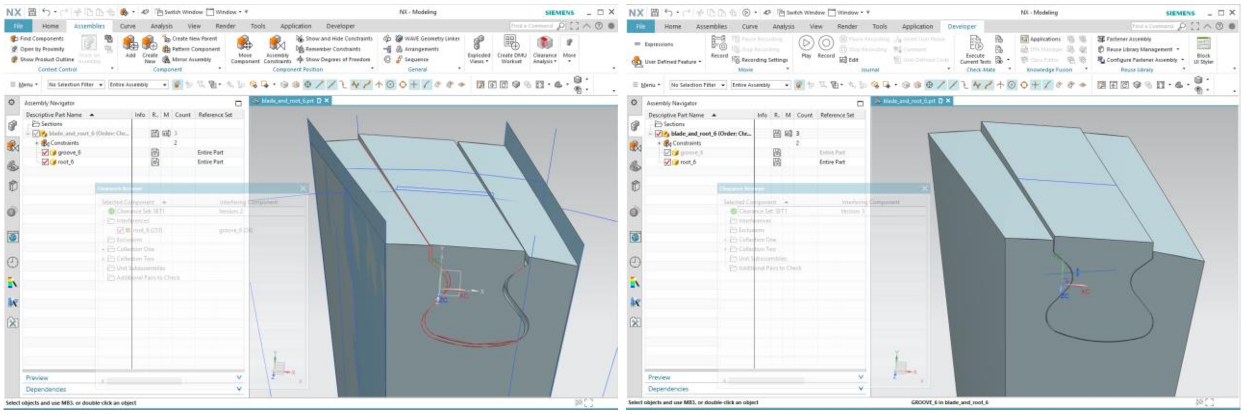


Figure 16. *Demonstration of the part aligner implemented as NXOpen Python journal*

During the DSE loop, modifications to the geometry occur both as input parameters (as-designed part) and a result of the simulations (as-manufactured part). When the geometry is altered, the exact position of the contact surfaces changes. Furthermore, it is not guaranteed that the as-manufactured root will still fit inside the groove (i.e., due to manufacturing deviations exceeding the allowed tolerance). While the mating simulation software addresses this issue in a robust and holistic way by solving the full six degrees of freedom problem between the two parts, that software requires both an extended run time and additional geometry processing to interface between NX CAD and OpenMETA.

To accelerate the DSE loop, an approximate part alignment tool was implemented (**Figure 16.** Demonstration of the part aligner implemented as NXOpen Python journal. This makes several assumptions regarding the two parts in order to skip a large amount of computational effort. First, it solves only two degrees of freedom by fixing the rotation and position along the groove (referred to here as the *z*-direction). In the present workflow, rotation will not change since the as-manufactured simulation is symmetric with respect to the root. Thus, rotation need not be updated between instances of the as-designed geometry. Likewise, the root and groove are assumed to be the same length and fixed with respect to the position along the groove. This is a safe assumption since the exterior faces are not currently modified by the as-manufactured surface simulation.

The part aligner operates in three steps. The first is a rough alignment using Linear Sum Assignment on a polygon defined by the cross-section of both root and groove parts in the *x*-*y* plane. This method places the exterior surface of the root near the interior surface of the groove but is not very accurate; this initial alignment typically results in overlap of the two parts.

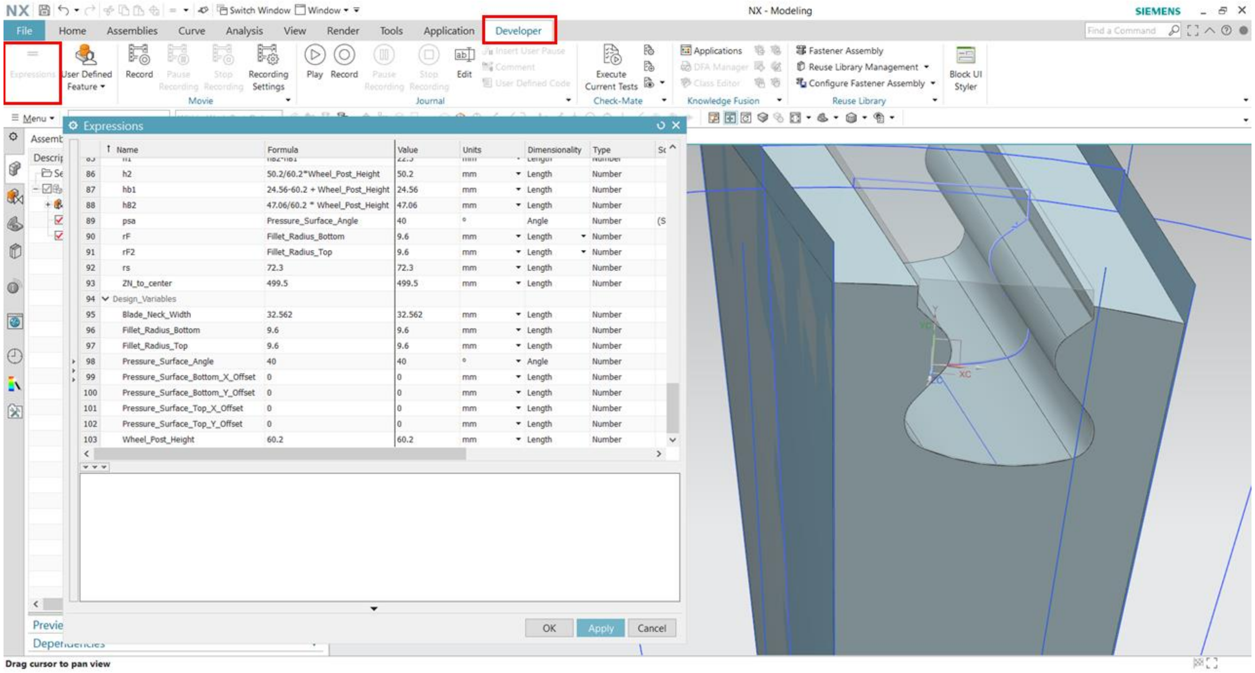
The next alignment step uses ray-casting to iteratively shift the root towards the center of the groove by computing the average ray from the surface of the root to any interior surfaces of the groove. This is achieved by uniformly and randomly sampling the surface of the root and computing the closest point on the groove. Only rays which strike the interior surface of the groove are considered, so the result is to shift the root in a direction which reduces the overlap.

This process is relatively fast (less than one second per iteration) so it is repeated several times until the magnitude of the proposed translation vector is small.

Finally, very fine adjustments to the position of the root are performed by a gradient-based minimization algorithm. The objective function is derived from the same calculation used in the ray-casting step: it is the sum of the magnitude of rays which strike the interior surfaces of the groove. When there are no rays that strike the interior surfaces (i.e., no overlap), it switches to the negative sum of the rays that strike the exterior surface. Therefore, when there are overlaps, this is a basic approximation of the overlap volume between the two parts, and when there are no overlaps then it is the negative of the volume in between the two parts. The gradient-based scheme converges quickly, typically running for only a few seconds when a non-overlapping arrangement is possible.

Expression update

The design parameters (e.g. blade neck width, fillet radii, wheel post heights), as well as the CAD parameters that represent the as-manufactured surface deflection (pressure surface offsets) were encoded as expressions in NX. These expressions values are updated during the design space exploration. **Figure 17** shows the expression window in NX graphical user interface (GUI).



	Name	Formula	Value	Units	Dimensionality	Type	Sc
86	h2	50.2/60.2*Wheel_Post_Height	50.2	mm	Length	Number	
87	hb1	24.56-60.2 + Wheel_Post_Height	24.56	mm	Length	Number	
88	hB2	47.06/60.2 * Wheel_Post_Height	47.06	mm	Length	Number	
89	psa	Pressure_Surface_Angle	40	°	Angle	Number	(S
90	rF	Fillet_Radius_Bottom	9.6	mm	Length	Number	
91	rF2	Fillet_Radius_Top	9.6	mm	Length	Number	
92	rs	72.3	72.3	mm	Length	Number	
93	ZN_to_center	499.5	499.5	mm	Length	Number	
94	Design_Variables						
95	Blade_Neck_Width	32.562	32.562	mm	Length	Number	
96	Fillet_Radius_Bottom	9.6	9.6	mm	Length	Number	
97	Fillet_Radius_Top	9.6	9.6	mm	Length	Number	
98	Pressure_Surface_Angle	40	40	°	Angle	Number	
99	Pressure_Surface_Bottom_X_Offset	0	0	mm	Length	Number	
100	Pressure_Surface_Bottom_Y_Offset	0	0	mm	Length	Number	
101	Pressure_Surface_Top_X_Offset	0	0	mm	Length	Number	
102	Pressure_Surface_Top_Y_Offset	0	0	mm	Length	Number	
103	Wheel_Post_Height	60.2	60.2	mm	Length	Number	

Figure 17: *Expression window in NX graphical user interface*

Since these expression updates have to be executed at each design update and as-manufactured surface generation during the design space exploration, an NX Open plug-in was generated to update these expressions in command prompt shell without launch the NX GUI upon each execution.

V. RESULTS

Use case description

The example use case is a design challenge derived from Siemens’ large gas turbine division. Large gas turbines are axial-flow turbomachines used by power companies to generate electricity for commercial and industrial customers. These highly engineered machines utilize many components operating under challenging conditions. One such component is a compressor stage bladed rotor disk with a dovetail attachment. The bladed rotor disk is comprised of two main components, a compressor blade and rotor disk (Error! Reference source not found.). The function of the compressor blade is to transmit mechanical energy to the working fluid (air) which presses the air into the downstream stationary vane resulting in an increase in pressure. Several compressor stages are attached in series allowing high flowrates and high overall pressure ratios. Pressurized air is mixed with a fuel to ignite combustion and subsequently extract power in the turbine stages. The compressor blade is attached to the rotor disk by means of a dovetail attachment. The dovetail attachment has two angled pressure faces which hold the compressor blade in place while the disk is rotating.

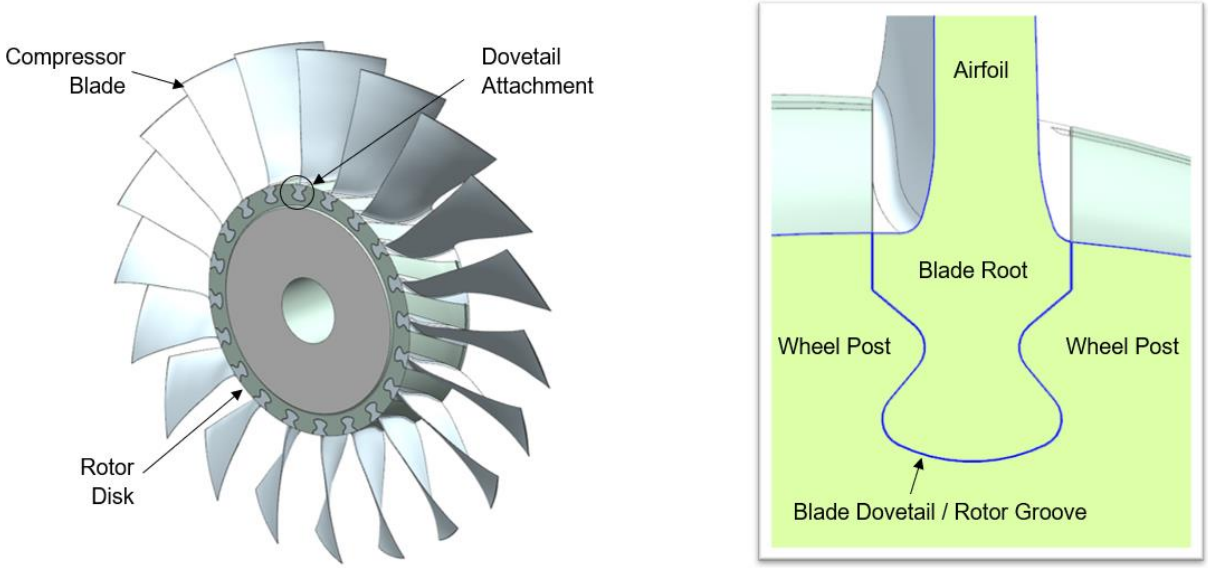


Figure 18: *Compressor Bladed Rotor Disk with Dovetail Attachment*

The design of dovetail attachment is a challenging problem. The airfoil and blade root pull on the dovetail attachment due to centrifugal force. Two angled pressure faces react to the centrifugal force onto the pressure faces of the mating rotor groove (**Figure 19**). The fit and surface quality of the blade root and rotor groove play an important role in the capability of the compressor bladed disk assembly.

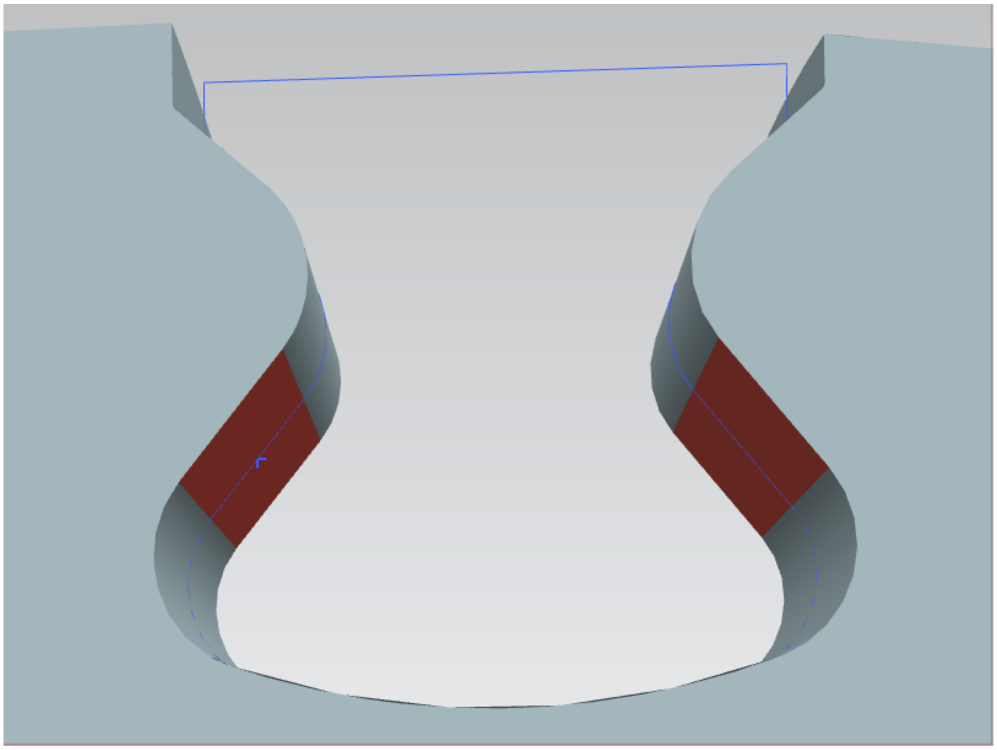


Figure 19: *Compressor wheel groove (dovetail-type) showing the pressure surfaces highlighted in red.*

Designing the blade/disk interface is a challenge due to numerous technical and manufacturing requirements. Today's design process requires design iteration to achieve technical requirements and only includes intermittent feedback from manufacturing to be included for design consideration. This process can result in the release of design geometry and design requirements which cause:

- Expensive tooling costs
- Excessive cutting times
- Excessive non-conformance costs
- Excessive rework
- Product fallout
- Engineering rework

The framework developed in this project allows design space exploration that integrates the assessment of design requirements and manufacturing capability, both of which are "in the loop" for each design iteration. This process allows quicker design/manufacturing feedback and has the potential to significantly reduce new product development time and overall product cost.

This test case simulates compressor wheel grooves cut with a profile cutter, a kind of milling tool that results in a particular angle or shape of cut. Such a mill bit is subject to stresses of its own under cutting load and is liable to deflect due to forces at the cutting interface (see **Figure 9**). As-manufactured grooves are likely to differ from as-designed grooves due in part to this effect. In real cases, manufacturing a new design of groove requires efforts to discover what specific tooling to use and the degree to which tool flex and other factors will cause differences between the as-manufactured part and the as-designed part.

The design variables chosen for the design space exploration are shown in **Table 3**. The variables control important dimensions relating to the function of the root-groove interface which a designer would want to manipulate in a traditional design process. **Figure 20** shows the sketch of the groove cross-section in the CAD model and Error! Reference source not found. shows the relationships between the dimensions in the CAD model and the design variables.

Table 3: *Design variables and their initial values and range of variation*

Design Variable	Value	Variation
Blade_Neck_Width	32.5	±20%
Fillet_Radius_Bottom	9.6	±30%
Fillet_Radius_Top	9.6	±30%
Pressure_Surface_Angle	40	±5°
Wheel_Post_Height	60.2	±30%

Table 4: *Design parameters, sketch dimensions, manufacturing analysis results, and relationships in the CAD model.*

Sketch Dimensions	
bB1	44.07-30.562+Blade_Neck_Width
bB2	45.93-30.562+Blade_Neck_Width
bH	53.4-30.562+Blade_Neck_Width
BN	58.37-30.562+Blade_Neck_Width
h1	hB2-hB1
h2	50.2/60.2 * Wheel_Post_Height
hb1	24.56-60.2 + Wheel_Post_Height
hB2	47.06/60.2 * Wheel_Post_Height
psa	Pressure_Surface_Angle
rF	Fillet_Radius_Bottom
rF2	Fillet_Radius_Top
ZN_to_center	499.5

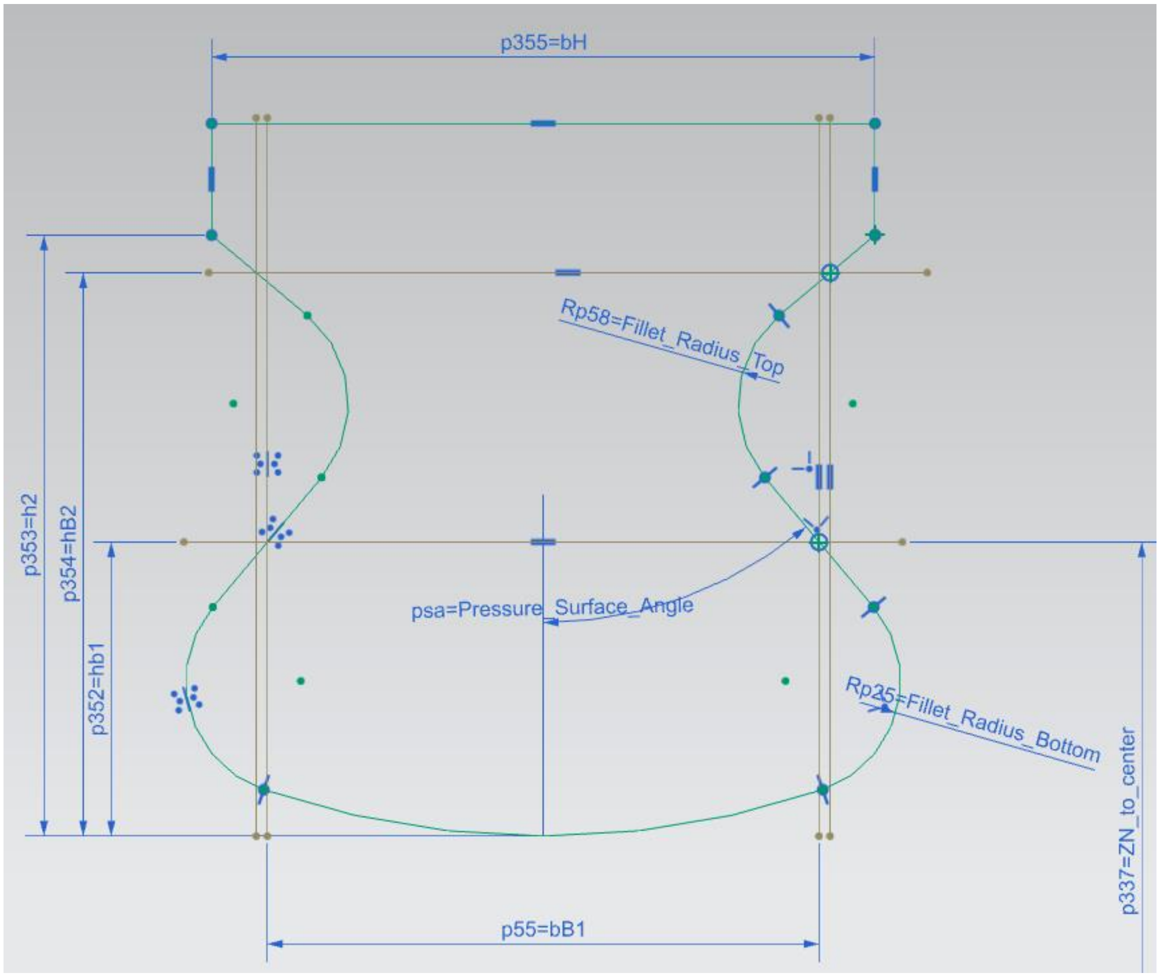


Figure 20: The sketch used for the cross section of the groove showing relevant controlled dimensions.

Once the new as-designed model is generated by manipulation of the design variables in OpenMETA, the manufacturing simulation is run and provides feedback regarding tool flex and displacement of the as-manufactured pressure surface from the nominal pressure surface as a result. These displacement results are returned to the CAD model as parameters via OpenMETA and update the model to an as-manufactured version. This as-manufactured groove part is then used in the analyses moving forward.

To evaluate the performance of the model, particularly the stress on the pressure surface between the blade root and the rotor groove, a thermal-mechanical simulation is run using Siemens NX. To reduce the computational cost, only a pie sector with single blade is modelled in the simulation, where cyclic symmetric boundary conditions (BC) are assumed, as shown in **Figure 21**. An axial constraint is imposed to prevent the dovetail from sliding out of the groove. The temperature boundary condition and loading condition is illustrated in **Figure 22**. The pressure surfaces between the rotor disk and the dovetail are also shown, where contact elements are defined in the setup.

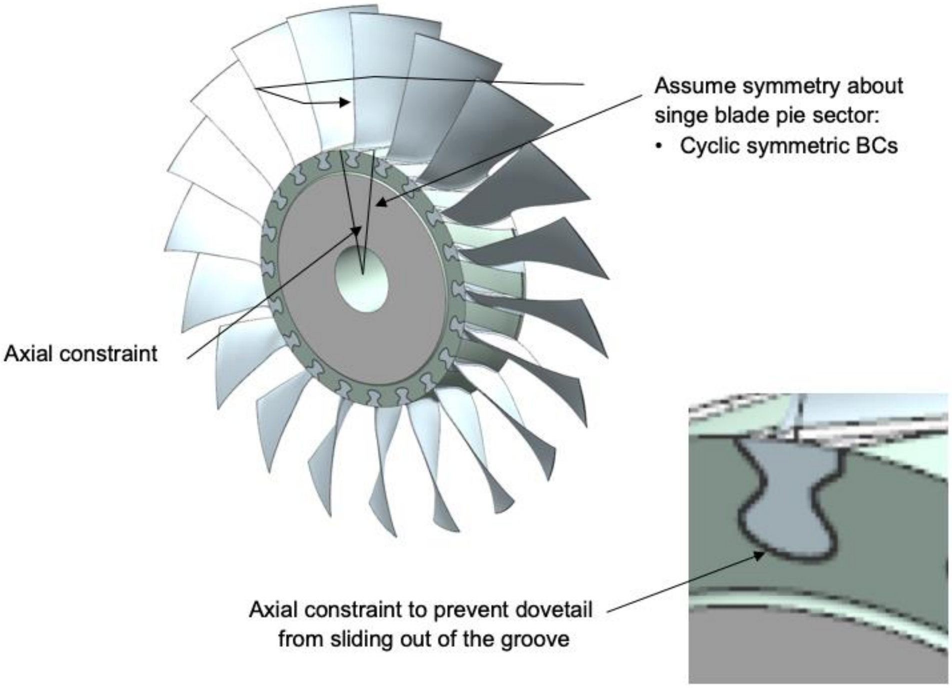


Figure 21: *Cyclic symmetric boundary condition assumption of the model.*

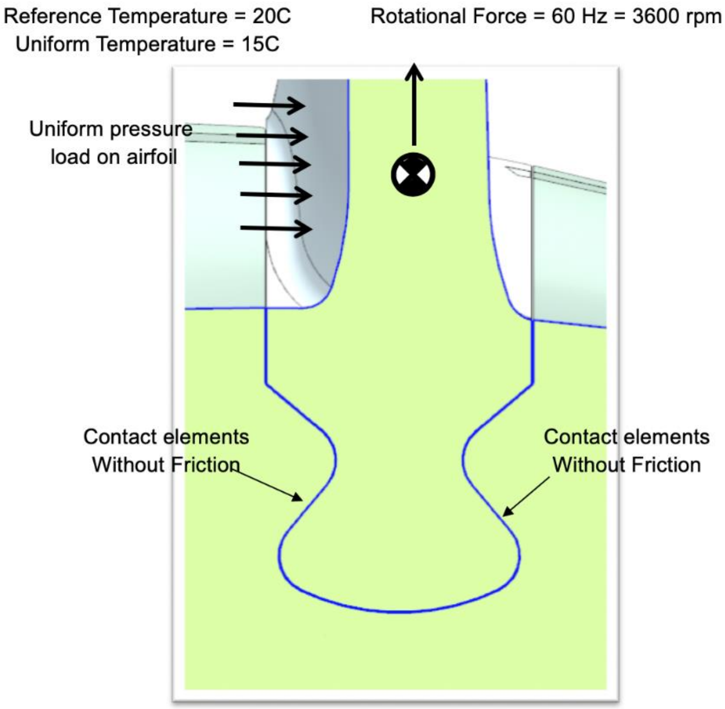


Figure 22: *Simulation model setup with boundary conditions.*

Since we are mostly interested in the contact stress on the pressure surfaces, only the root part of the dovetail is modelled in the simulation, while the blade part is simplified as a mass element. The mass element is then connected to the blade root using rigid body elements. The aerodynamic force caused by the rotation is then directly imposed on the mass element, as shown in **Figure 23**. The final simulation model with mesh is shown in **Figure 24**.

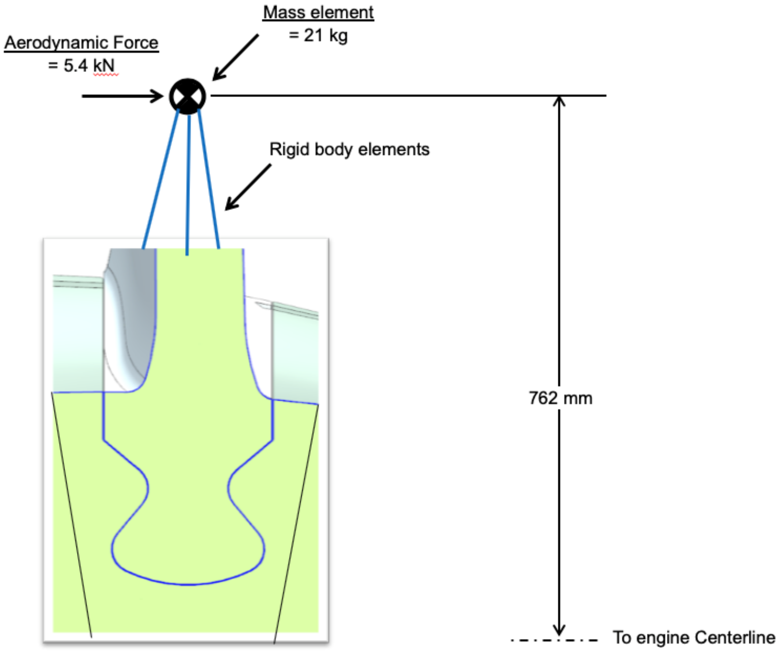


Figure 23: *Simplified model setup.*

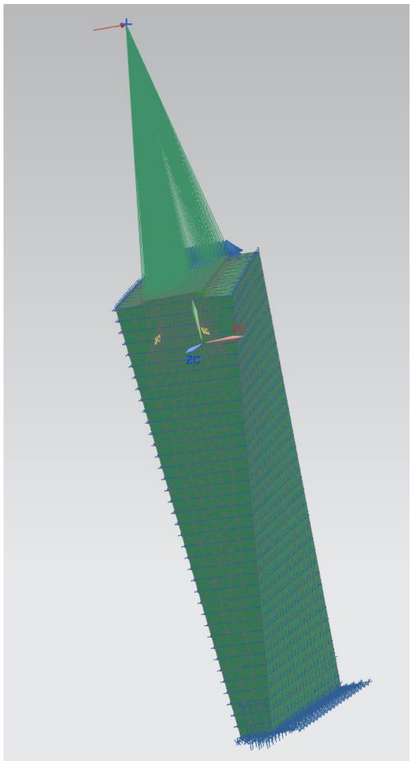


Figure 24: *Final simulation model with boundary conditions in Siemens NX.*

Due to a NX license restriction, we are limited in using the linear statics solver with global constraints for this model. **Figure 25** shows the stress of the dovetail and rotor from the simulation result. The result looks to be loading up the pressure faces as defined. However, the gas load seems creating significant bending at the joint. We suspect the reason is that, the linear analysis solver we are using cannot handle the contact good enough as the non-linear analysis, which would iterate until a converged solution is reached to resolve the contact.

Nonetheless it successfully demonstrates that the FE simulation can be run with the given CAD model and the simulation results can be retrieved by OpenMETA for design space exploration. Once the favorable non-linear solver is available, it can easily be switched over without changing the overall workflow.

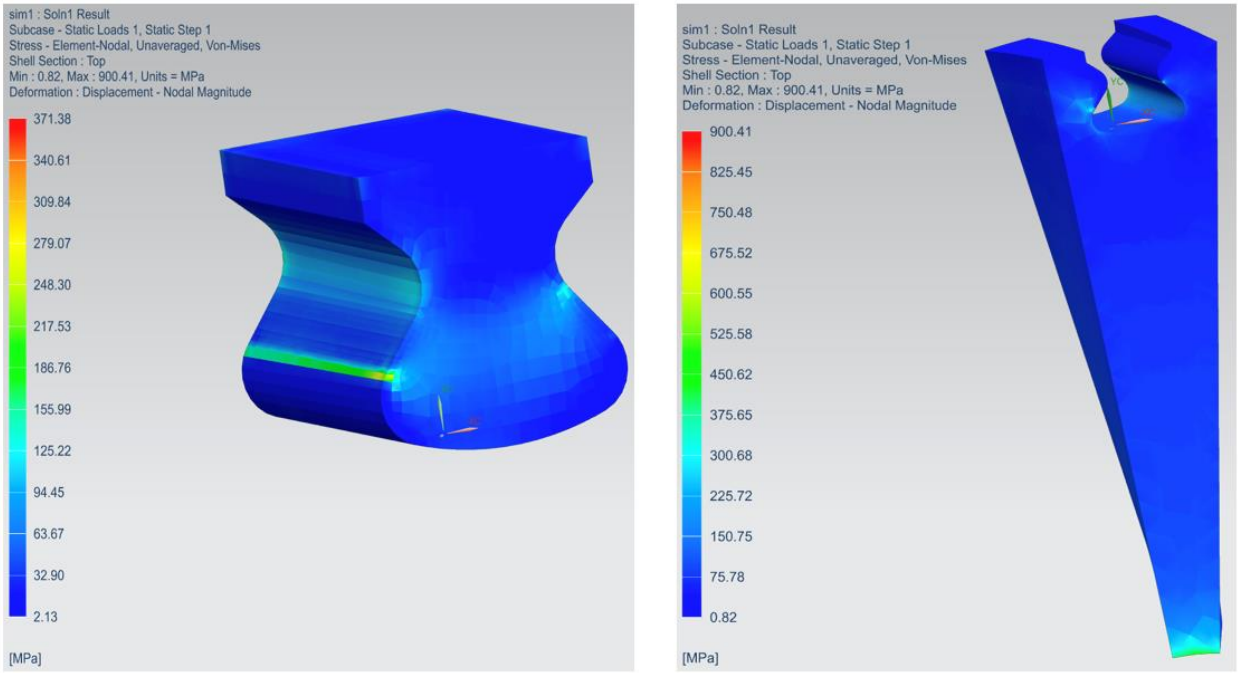


Figure 25: *Simulation results showing the stress distribution of the dovetail and rotor.*

Target Users & Modes of Operation

The target users for this tool are summarized in **Table 5** below. All users listed below would have input and/or checking responsibilities of the tool. In addition to the benefits outlined in the use case description, this tool would significantly reduce the amount of interaction time among the users. Most likely, one member of the user group would be responsible for executing the process. This member would be required to collect inputs and ensure checking of results by other members with the appropriate expertise.

Table 5: *Target end users*

JOB TITLE	DESCRIPTION	EXPERTISE
Compressor Blade Design Engineer	Early career to senior level engineer with experience in mechanical design of axial compressor blades and vanes	Compressor blade and vane design, fits and stack-ups, DOE methods
Rotor Design Engineer	Early career to senior level engineer with experience in mechanical design of rotating disks	Compressor rotor design, fits and stack-ups, DOE methods
Product Definer	Early career to senior level CAD modeler with experience in modeling of axial compressor blades, vanes, and rotors	Compressor blade, vane, and rotor NX CAD modeling, parametric modeling

Structural Integrity Engineer	Early career to senior level analyst with experience in finite element modeling of axial compressor blades, vanes, and rotors	Compressor blade, vane, and rotor finite element modeling
Manufacturing Engineer	Early career to senior level analyst with experience in manufacturing of blade roots and rotor disks	Compressor blade manufacturing, Compressor disk manufacturing, milling techniques, tooling design

DSE WORKFLOW FOR THE USE CASE

The DSE Workflow for this use case was implemented in OpenMETA. The workflow in **Figure 26** is driven by the Parametric Study driver (on the left in **Figure 26**). The Parametric Study driver selects the design and manufacturing parameter values for each invocation of the workflow according to a uniform sampling method.

For each analysis we want to run on the model in the OpenMETA framework, we set up a TestBench that operates on the system model, in this case the Rotor Disk and Blade Root.

The workflow begins with the execution of the GIFT tool generating the as-manufactured surfaces for the geometry according to the selected manufacturing parameters for this invocation and produces the geometrical deviations due to manufacturing processes. These manufacturing geometric deviations are sent to NX CAD. NX CAD parametrically modifies the geometry appropriately to reflect the manufacturing effects on the surface of the part.

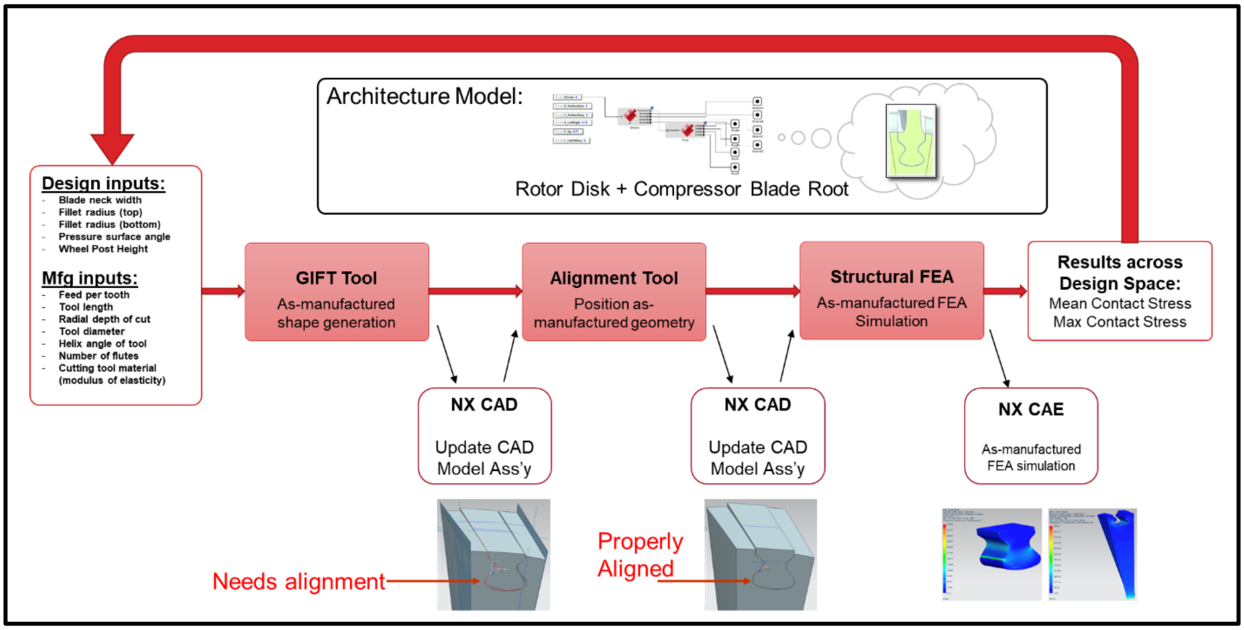


Figure 26: *DSE Workflow in OpenMETA for this use case*

At this point in the workflow, the nominal geometry has been modified to represent the as-manufactured geometry. Since we modified the geometry, the relative position of the rotor disk and blade is not properly aligned for a structural analysis. The part alignment tool is now executed to align the parts into their "loaded" contact position using NX CAD as its engine to perform the geometric computations. Now the rotor/blade geometry is ready for input to the structural analysis and is sent to the NX CAE Nastran analysis computing the max contact stress and mean contact stress. We also record other computed values that are useful for "debugging the analysis" such as the length of the pressure face.

The DSE data flow for this use case is also shown in **Figure 27**. Starting in NX CAD, part geometries are parameterized according to the design parameters (and expressions defined for those parts) to yield the as-designed part file or nominal geometry to be modified subsequently.

The as-designed CAD model and design parameters, and manufacturing process parameters are inputs to the As-manufactured shape generation module that generates the as-manufactured geometry with known manufacturing-induced form errors. Next, the CAD parts of the designs are automatically assembled and the resulting assembly is input into a custom-purpose built alignment tool. The alignment tool's function is to compute the relative positioning of the parts to represent their mating alignment as needed to drive the stress analysis.

The results are made available in a *.csv file containing the metrics computed for the parametric variations of the workflow across the sets of design and manufacturing parameters of interest.

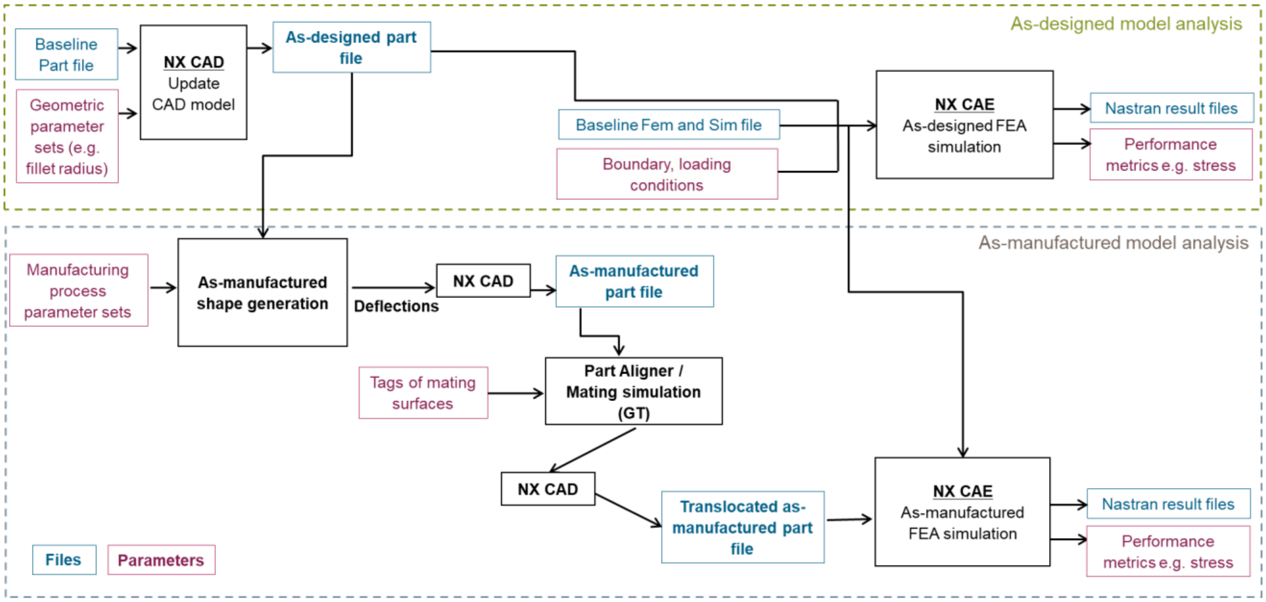
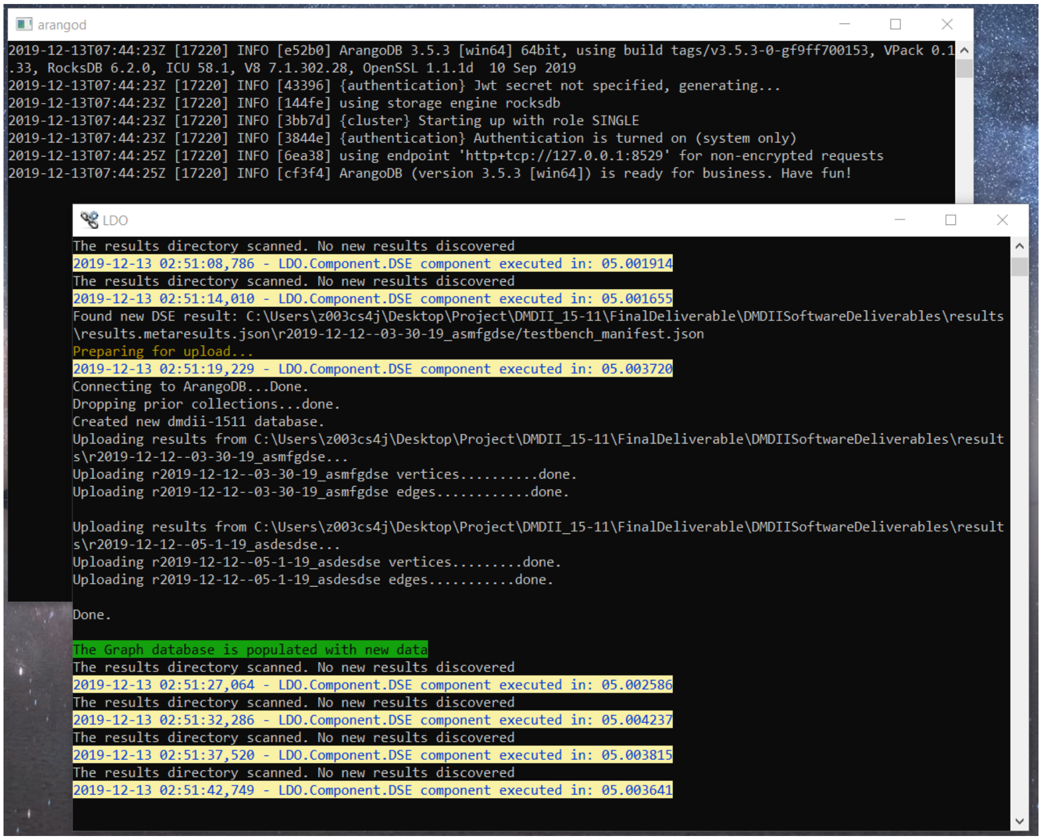


Figure 27: *Design Space Exploration workflow*

Linked Data Framework

Upon completion of a DSE run, Linked Data Orchestrator (LDO) will upload the DSE results to ArangoDB for subsequent queries. **Figure 28** illustrates the output from LDO when as-designed DSE run ("r2019-12-12--05-1-19_asdesdse") and as-manufactured DSE run are being completed ("r2019-12-12--03-30-19_asmfgdse") and results are being uploaded to ArangoDB.



```
2019-12-13T07:44:23Z [17220] INFO [e52b0] ArangoDB 3.5.3 [win64] 64bit, using build tags/v3.5.3-0-gf9ff700153, VPack 0.1
.33, RocksDB 6.2.0, ICU 58.1, V8 7.1.302.28, OpenSSL 1.1.1d  10 Sep 2019
2019-12-13T07:44:23Z [17220] INFO [43396] {authentication} Jwt secret not specified, generating...
2019-12-13T07:44:23Z [17220] INFO [144fe] using storage engine rocksdb
2019-12-13T07:44:23Z [17220] INFO [3bb7d] {cluster} Starting up with role SINGLE
2019-12-13T07:44:23Z [17220] INFO [3844e] {authentication} Authentication is turned on (system only)
2019-12-13T07:44:25Z [17220] INFO [6ea38] using endpoint 'http+tcp://127.0.0.1:8529' for non-encrypted requests
2019-12-13T07:44:25Z [17220] INFO [cf3f4] ArangoDB (version 3.5.3 [win64]) is ready for business. Have fun!
```

```
The results directory scanned. No new results discovered
2019-12-13 02:51:08,786 - LDO.Component.DSE component executed in: 05.001914
The results directory scanned. No new results discovered
2019-12-13 02:51:14,010 - LDO.Component.DSE component executed in: 05.001655
Found new DSE result: C:\Users\z003cs4j\Desktop\Project\DMDII_15-11\FinalDeliverable\DMDIISoftwareDeliverables\results
\results.metaresults.json\r2019-12-12--03-30-19_asmfgdse/testbench_manifest.json
Preparing for upload...
2019-12-13 02:51:19,229 - LDO.Component.DSE component executed in: 05.003720
Connecting to ArangoDB...Done.
Dropping prior collections...done.
Created new dmdii-1511 database.
Uploading results from C:\Users\z003cs4j\Desktop\Project\DMDII_15-11\FinalDeliverable\DMDIISoftwareDeliverables\result
s\r2019-12-12--03-30-19_asmfgdse...
Uploading r2019-12-12--03-30-19_asmfgdse vertices..........done.
Uploading r2019-12-12--03-30-19_asmfgdse edges...........done.

Uploading results from C:\Users\z003cs4j\Desktop\Project\DMDII_15-11\FinalDeliverable\DMDIISoftwareDeliverables\result
s\r2019-12-12--05-1-19_asdesdse...
Uploading r2019-12-12--05-1-19_asdesdse vertices.........done.
Uploading r2019-12-12--05-1-19_asdesdse edges..........done.

Done.

The Graph database is populated with new data
The results directory scanned. No new results discovered
2019-12-13 02:51:27,064 - LDO.Component.DSE component executed in: 05.002586
The results directory scanned. No new results discovered
2019-12-13 02:51:32,286 - LDO.Component.DSE component executed in: 05.004237
The results directory scanned. No new results discovered
2019-12-13 02:51:37,520 - LDO.Component.DSE component executed in: 05.003815
The results directory scanned. No new results discovered
2019-12-13 02:51:42,749 - LDO.Component.DSE component executed in: 05.003641
```

Figure 28: *LDO detects the new results being populated and upload data to ArangoDB graph database*

By exploring the correlations between design, manufacturing and performance parameters (mean and maximum contact stress), a knowledge graph involving these parameters is being constructed with ArangoDB. Each node represents a given design/manufacturing/performance parameter and an edge denotes the relationships between nodes. As illustrated in **Figure 29**, the interplay between design and manufacturing parameters can be demonstrated to identify key design and manufacturing parameters that might affect the performance parameters to advice on future designs.

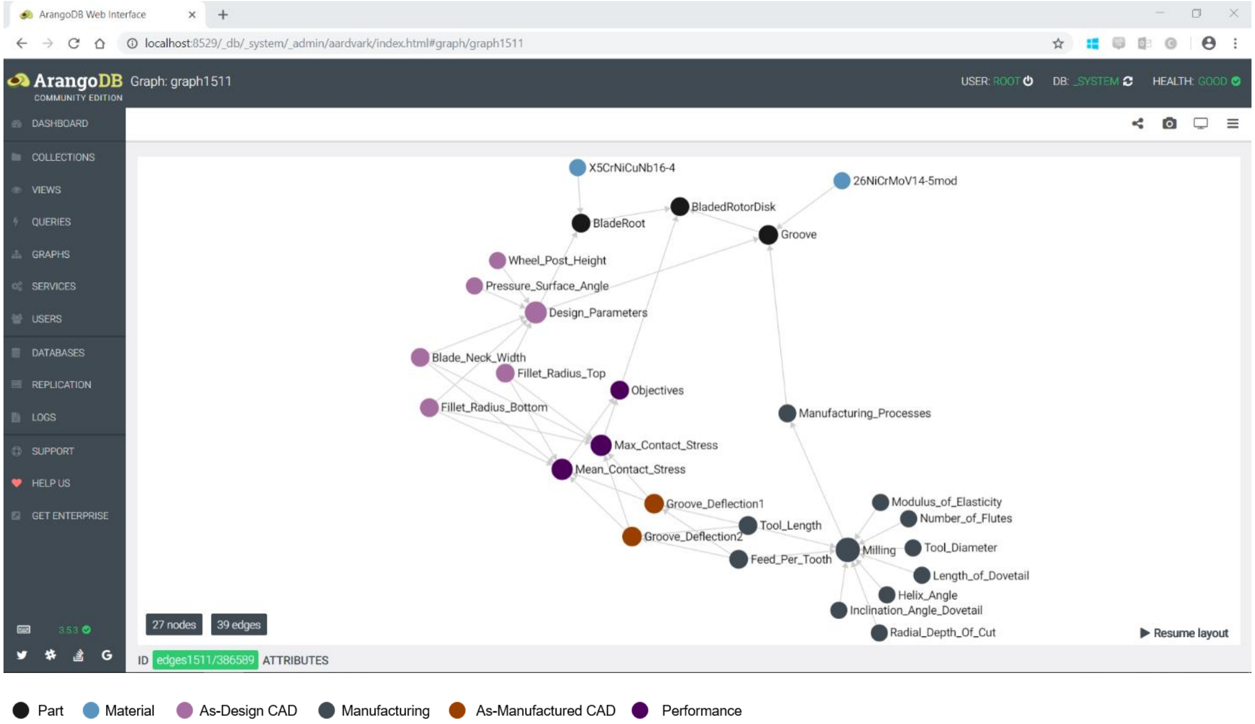
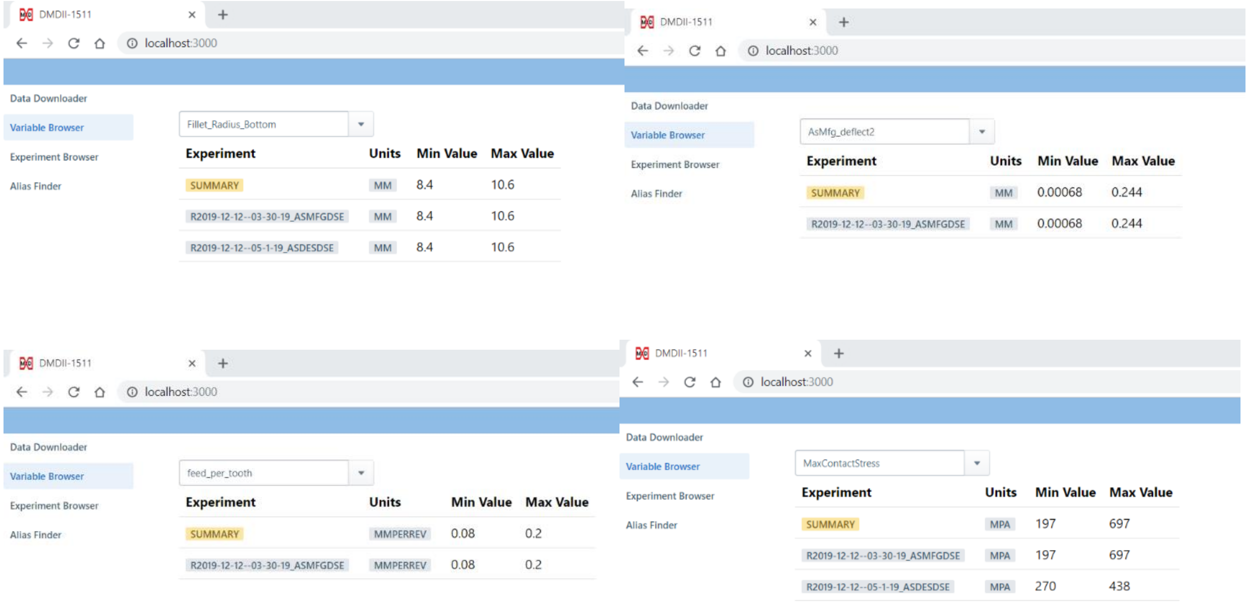


Figure 29: *Knowledge graph to illustrate relationships between design, manufacturing and performance parameters*

The Knowledge Portal is a JavaScript web client implemented using the React library. It serves as a client-side user interface to access the Knowledge Graph stored in Arango DB in a visual/interactive fashion and without requirement for the user to formulate AQL requests. The React components provide responsive visual feedback as requests are made to and responses are received from the Arango DB Knowledge Graph via the Flask application.

The main capabilities of the Knowledge Portal are quickly screening the prior DSE stored in the Knowledge Graph. With the **Data Downloader**, the results from common variables between different DSE can be downloaded as a single CSV. With the **Variable Browser (Figure 30)**, the values of a selected variable can be evaluated for all DSE in which that variable appears. The **Experiment Browser (Figure 31)** shows all DSE in the Knowledge Graph with the variables categorized by their role in the OpenMETA Test Bench. The **Alias Finder** (**Figure 32**) compares DSE to identify possible aliases between variables.



Fillet_Radius_Bottom

Experiment	Units	Min Value	Max Value
SUMMARY	MM	8.4	10.6
R2019-12-12--03-30-19_ASMFGDSE	MM	8.4	10.6
R2019-12-12--05-1-19_ASDESDSE	MM	8.4	10.6

AsMfg_deflect2

Experiment	Units	Min Value	Max Value
SUMMARY	MM	0.00068	0.244
R2019-12-12--03-30-19_ASMFGDSE	MM	0.00068	0.244

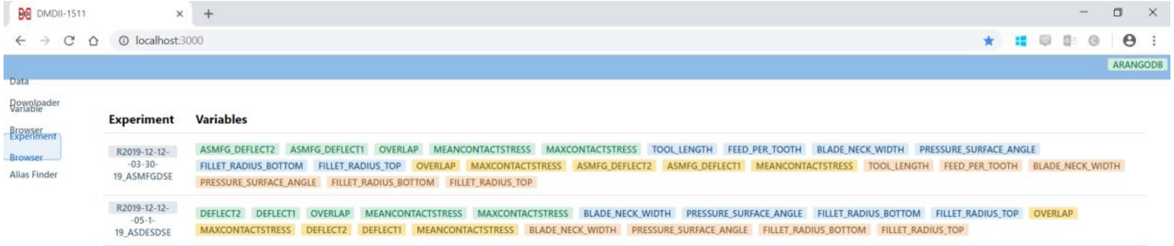
feed_per_tooth

Experiment	Units	Min Value	Max Value
SUMMARY	MMPERREV	0.08	0.2
R2019-12-12--03-30-19_ASMFGDSE	MMPERREV	0.08	0.2

MaxContactStress

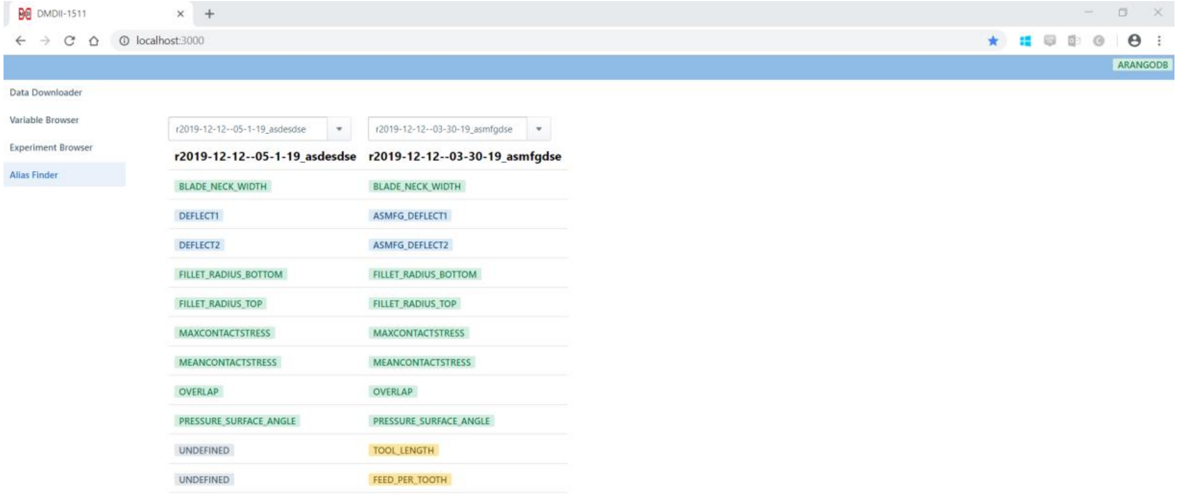
Experiment	Units	Min Value	Max Value
SUMMARY	MPA	197	697
R2019-12-12--03-30-19_ASMFGDSE	MPA	197	697
R2019-12-12--05-1-19_ASDESDSE	MPA	270	438

Figure 30: *Variable Browser - Search for values and units of common variables across multiple DSE*



Experiment	Variables
R2019-12-12--03-30-19_ASMFGDSE	ASMFG_DEFLECT2 ASMFG_DEFLECT1 OVERLAP MEANCONTACTSTRESS MAXCONTACTSTRESS TOOL_LENGTH FEED_PER_TOOTH BLADE_NECK_WIDTH PRESSURE_SURFACE_ANGLE FILLET_RADIUS_BOTTOM FILLET_RADIUS_TOP OVERLAP MAXCONTACTSTRESS ASMFG_DEFLECT2 ASMFG_DEFLECT1 MEANCONTACTSTRESS TOOL_LENGTH FEED_PER_TOOTH BLADE_NECK_WIDTH PRESSURE_SURFACE_ANGLE FILLET_RADIUS_BOTTOM FILLET_RADIUS_TOP
R2019-12-12--05-1-19_ASDESDSE	DEFLECT2 DEFLECT1 OVERLAP MEANCONTACTSTRESS MAXCONTACTSTRESS BLADE_NECK_WIDTH PRESSURE_SURFACE_ANGLE FILLET_RADIUS_BOTTOM FILLET_RADIUS_TOP OVERLAP MAXCONTACTSTRESS DEFLECT2 DEFLECT1 MEANCONTACTSTRESS BLADE_NECK_WIDTH PRESSURE_SURFACE_ANGLE FILLET_RADIUS_BOTTOM FILLET_RADIUS_TOP

Figure 31: *Experiment Browser - Quickly and visually explore the different sets of DSE*

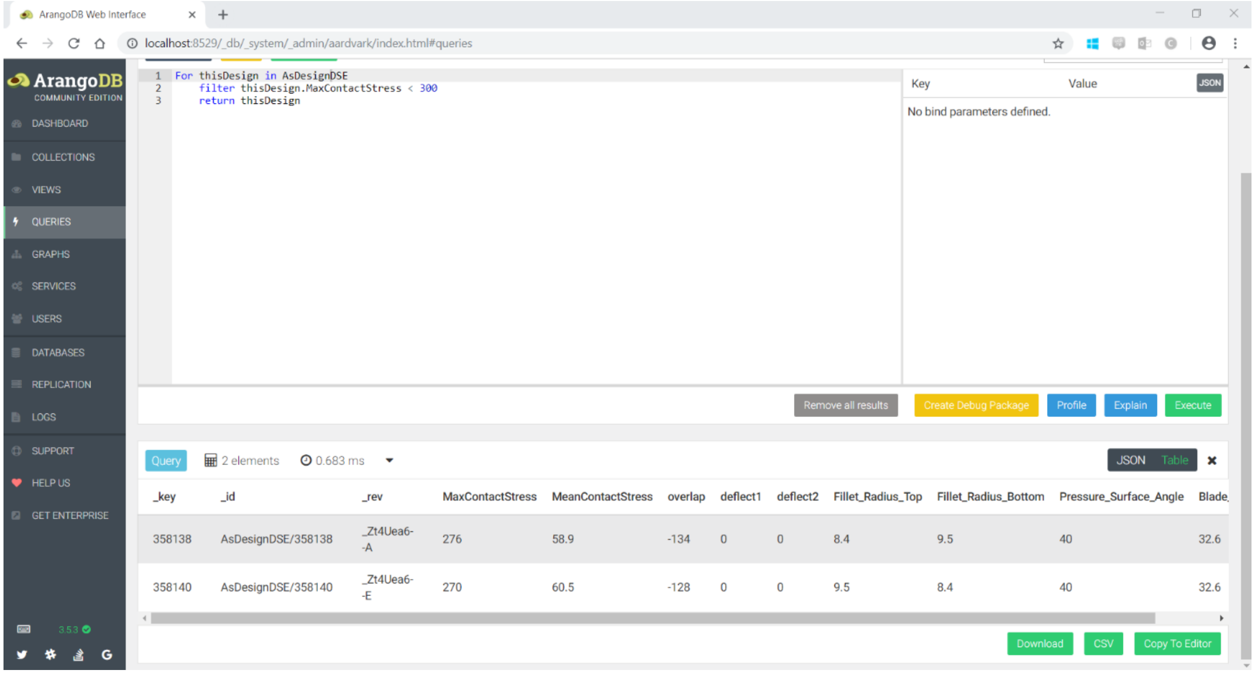


r2019-12-12--05-1-19_asdesdse	r2019-12-12--03-30-19_asmfgdse
BLADE_NECK_WIDTH	BLADE_NECK_WIDTH
DEFLECT1	ASMFG_DEFLECT1
DEFLECT2	ASMFG_DEFLECT2
FILLET_RADIUS_BOTTOM	FILLET_RADIUS_BOTTOM
FILLET_RADIUS_TOP	FILLET_RADIUS_TOP
MAXCONTACTSTRESS	MAXCONTACTSTRESS
MEANCONTACTSTRESS	MEANCONTACTSTRESS
OVERLAP	OVERLAP
PRESSURE_SURFACE_ANGLE	PRESSURE_SURFACE_ANGLE
UNDEFINED	TOOL_LENGTH
UNDEFINED	FEED_PER_TOOTH

Figure 32: *Alias Finder - Identify variables which take different names between DSE*

DSE Queries

Screenshots captured in **Figure 33**, **Figure 34**, **Figure 35** provide an example of the type of queries that can be performed in the Knowledge Portal. Specific queries that were used to analyze results from the DSE run are discussed in the Discussion and Analysis section under DSE Results c) Enriching Design Space Exploration with Manufacturing Information

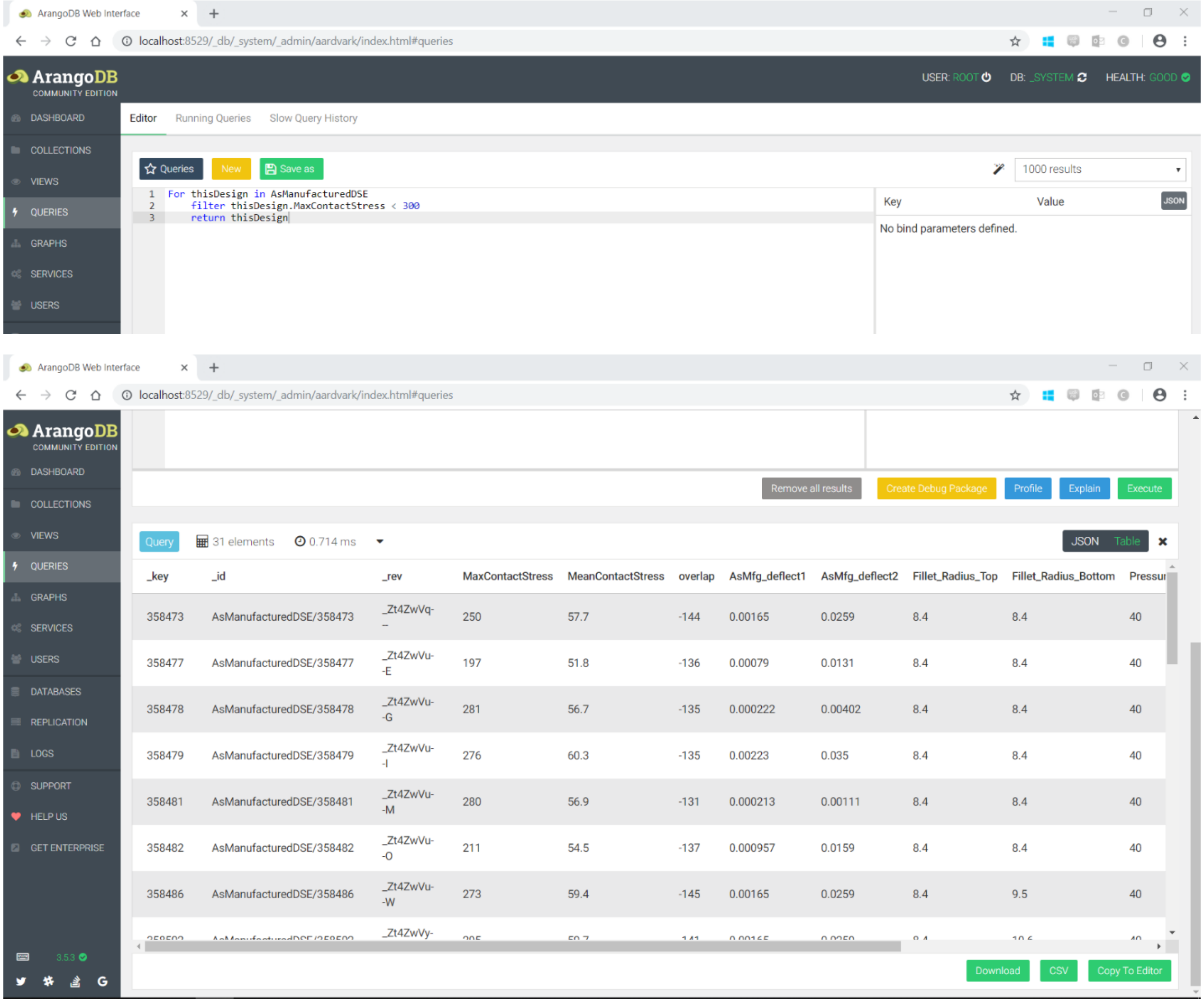


```
For thisDesign in AsDesignDSE
    filter thisDesign.MaxContactStress < 300
    return thisDesign
```

No bind parameters defined.

_key	_id	_rev	MaxContactStress	MeanContactStress	overlap	deflect1	deflect2	Fillet_Radius_Top	Fillet_Radius_Bottom	Pressure_Surface_Angle	Blade_
358138	AsDesignDSE/358138	_Zt4Uea6--A	276	58.9	-134	0	0	8.4	9.5	40	32.6
358140	AsDesignDSE/358140	_Zt4Uea6--E	270	60.5	-128	0	0	9.5	8.4	40	32.6

Figure 33: *As Designed DSE – Query design parameters that meet requirements*

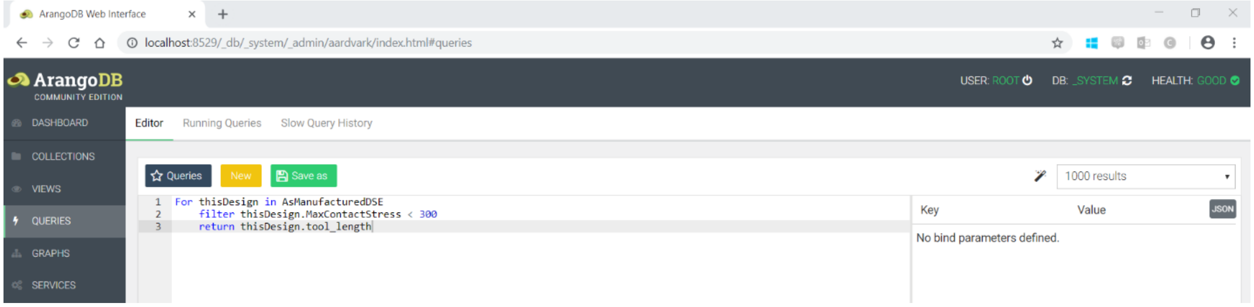


```
For thisDesign in AsManufacturedDSE
    filter thisDesign.MaxContactStress < 300
    return thisDesign
```

No bind parameters defined.

_key	_id	_rev	MaxContactStress	MeanContactStress	overlap	AsMfg_deflect1	AsMfg_deflect2	Fillet_Radius_Top	Fillet_Radius_Bottom	Pressu
358473	AsManufacturedDSE/358473	_Zt4ZwVq-_	250	57.7	-144	0.00165	0.0259	8.4	8.4	40
358477	AsManufacturedDSE/358477	_Zt4ZwVu--E	197	51.8	-136	0.00079	0.0131	8.4	8.4	40
358478	AsManufacturedDSE/358478	_Zt4ZwVu--G	281	56.7	-135	0.000222	0.00402	8.4	8.4	40
358479	AsManufacturedDSE/358479	_Zt4ZwVu--I	276	60.3	-135	0.00223	0.035	8.4	8.4	40
358481	AsManufacturedDSE/358481	_Zt4ZwVu--M	280	56.9	-131	0.000213	0.00111	8.4	8.4	40
358482	AsManufacturedDSE/358482	_Zt4ZwVu--O	211	54.5	-137	0.000957	0.0159	8.4	8.4	40
358486	AsManufacturedDSE/358486	_Zt4ZwVu--W	273	59.4	-145	0.00165	0.0259	8.4	9.5	40

Figure 34: *As Manufactured DSE – Query design parameters that meet requirements*



```
For thisDesign in AsManufacturedDSE
    filter thisDesign.MaxContactStress < 300
    return thisDesign.tool_length
```

No bind parameters defined.

Figure 35: *As Manufactured DSE – Query list of feasible tool lengths parameters*

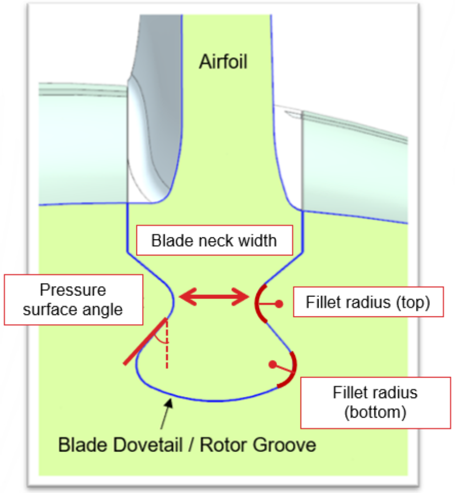
VI. DISCUSSION AND ANALYSIS

In this section, design space exploration of the bladed rotor risk will be performed with and without accounting for manufacturing variations. Given that a number of design and manufacturing parameters are involved, here we down-select a subset of those to illustrate the DSE and linked data framework.

The design variables and manufacturing variables being varied in the DSE demonstration are listed in the **Table 6**. Each of these variables was being varied independently of the others to each sample 11 evenly-distributed design points across the ranges.

Table 6: *Design and manufacturing variables*

Design Variable	**Baseline value**	**Variations**
Blade Neck Width	32.562	22.79 – 42.33
Fillet Radius Bottom	9.6	8.6-10.6
Fillet Radius Top	9.6	8.6-10.6
Pressure Surface Angle	40	35-45
Wheel Post Height	60.2	(Constant)
Manufacturing Variable	**Baseline value**	**Variations**
Num. of flutes	2	(Constant)
Feed per tooth	0.08	0.08-0.2
Tool diameter	52	(Constant)
Tool length	178.45	75-200
Helix angle	20.79	(Constant)
Modulus of elasticity	700000	(Constant)
Radial depth of cut	1	(Constant)



In addition, the analysis results discussed here were performed outside of the OpenMETA DSE framework given the time constraint. However, in both cases the DSE results shall produce similar trends.

DSE Results

a) Design Space Exploration

The correlations between design parameters (blade neck width, fillet radii and pressure surface angle) and performance metrics (mean and maximum contact stresses) are plotted in the following figures (**Figure 36** and **Figure 37**) from the DSE results (excluding manufacturing variations). Positive trend between blade neck width and stress metrics, and between fillet radius (bottom) and stress metrics are observed. There also exists positive relation between fillet radius (top) and mean contact stress.

Relationships between Design Parameters and Mean Contact Stress

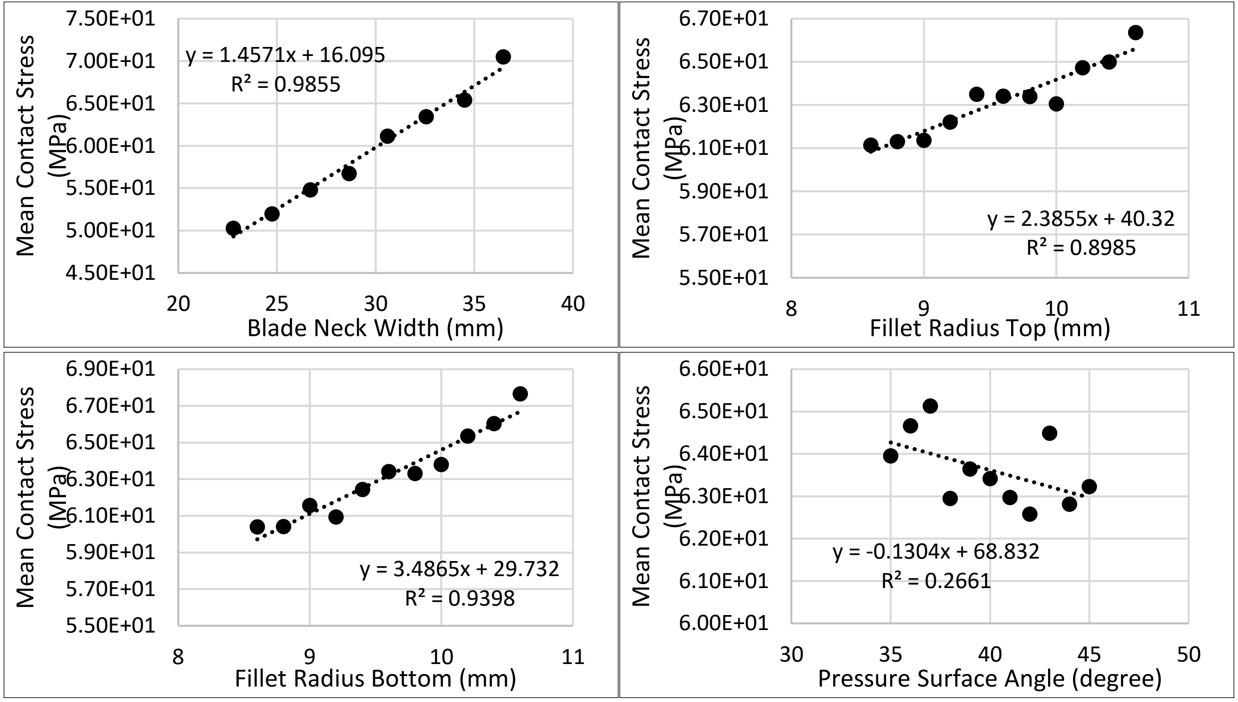


Figure 36: *Correlations between design parameters and mean contact stresses*

Relationships between Design Parameters and Max Contact Stress

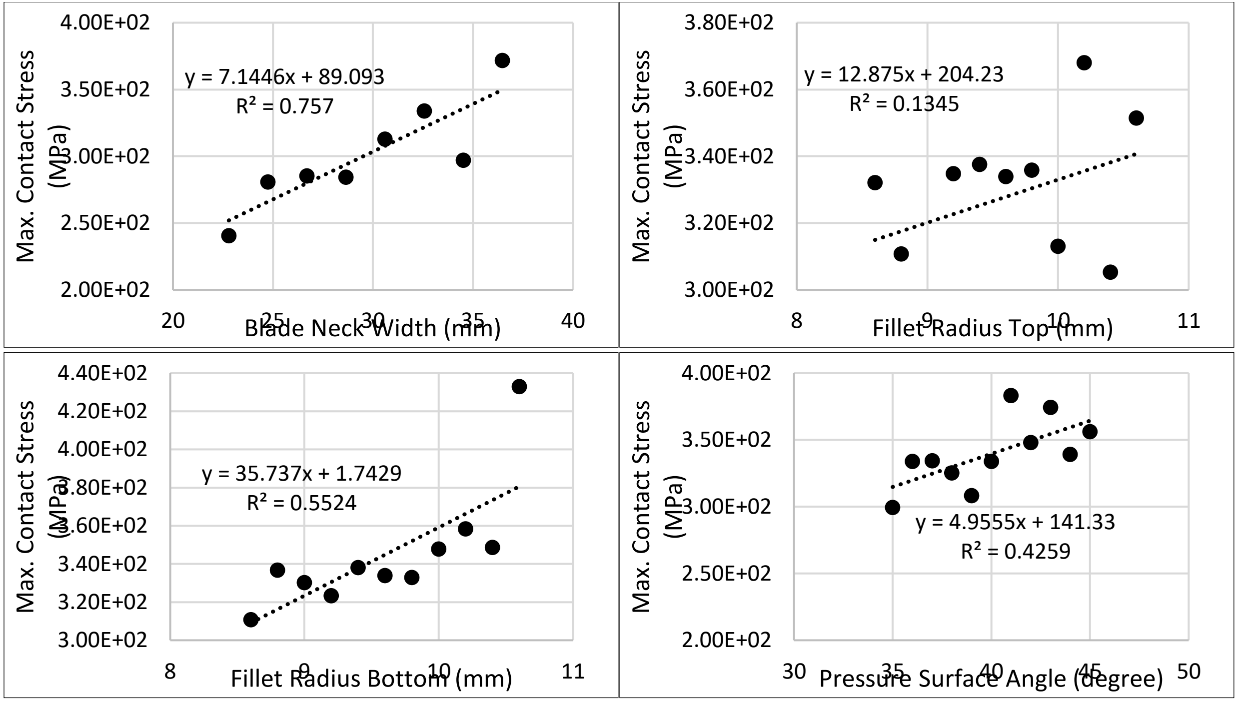


Figure 37: *Correlations between design parameters and maximum contact stresses*

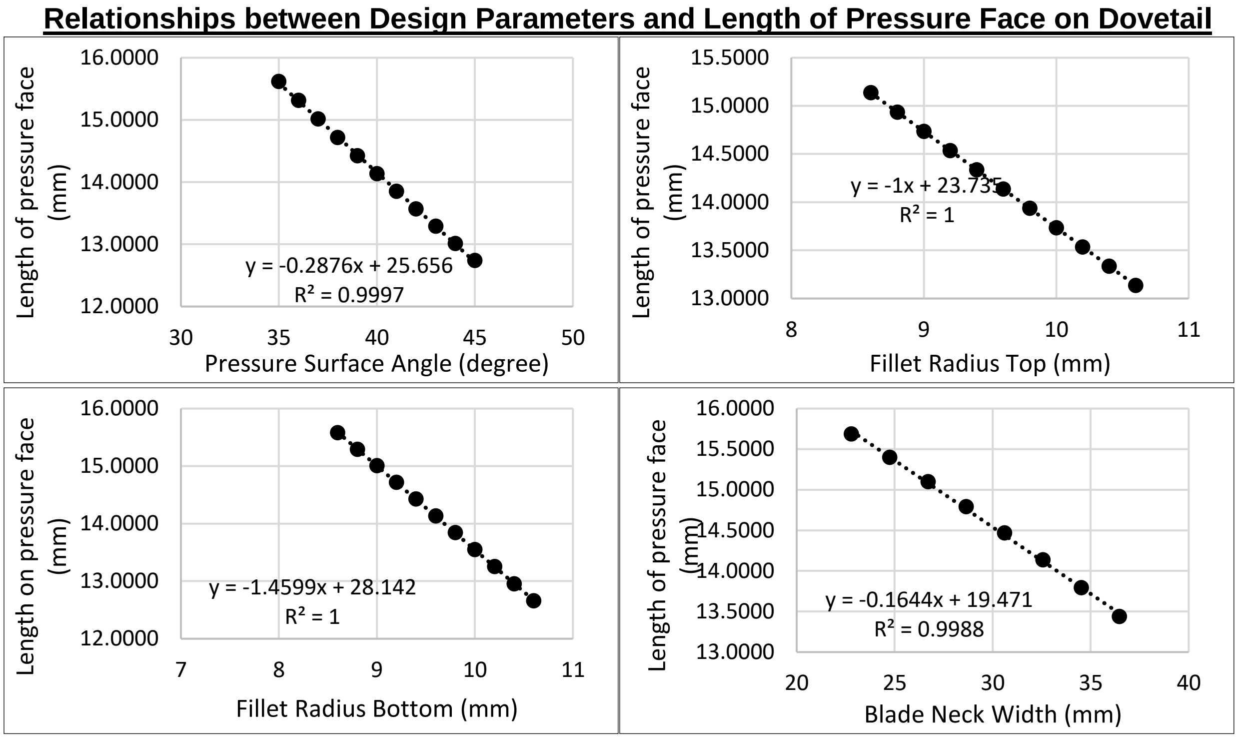


Figure 38: *Correlations between design parameters and length of pressure face on dovetail*

To better understand the relationship between design parameters and stress metrics, the length of pressure face on the groove was being quantified. Negative correlations between length of pressure face and the selected design parameters are observed (**Figure 38**). This helps explain the positive relationship between design parameters (blade neck width and filet radii) and contact stress. As these design parameters increase, the resultant length of pressure face decreases, which in turn reduces the contact surface area and elevating the resulting stresses.

b) Design and Manufacturing Space Exploration

Manufacturing deviation on the groove was being accounted for by offsetting the end points of the pressure surface by amount computed by the GIFT tool based on given manufacturing parameters. Feed per tooth (**Figure 39**) and tool length (**Figure 40**) were being varied parametrically in the design and manufacturing space exploration. Positive relationships were observed between these manufacturing parameters and maximum deflection on the pressure face. This was due to the increase in milling forces, causing larger deflection on the pressure face (computed with GIFT tool). This in turn reduces the length of pressure face and increases mean and maximum contact stresses.

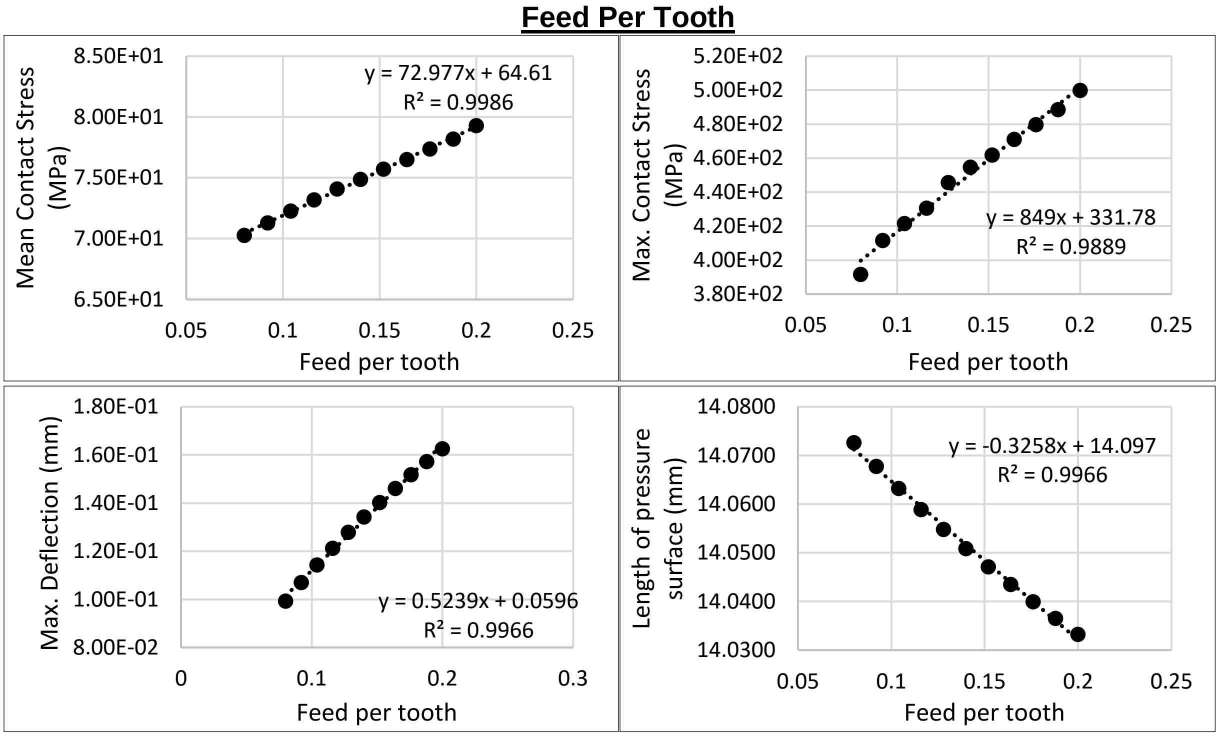


Figure 39: *Correlations between feed per tooth, contact stresses, maximum pressure face deflection and length of pressure surface*

Tool Length

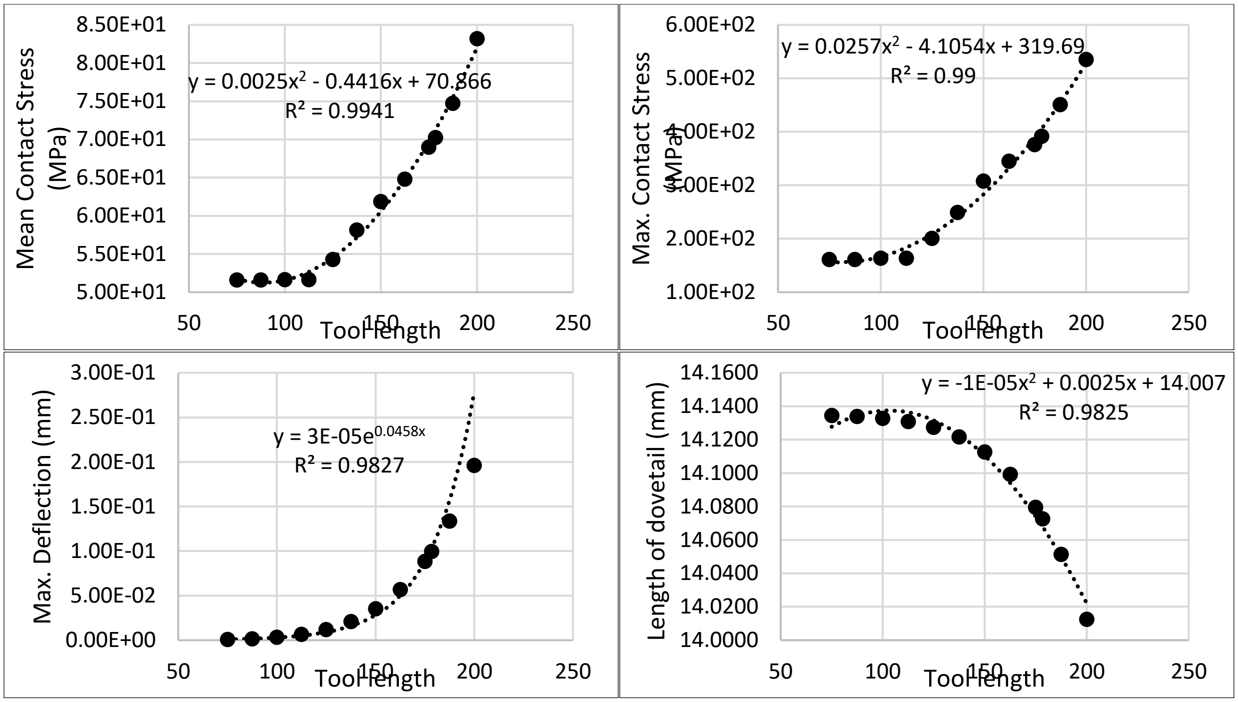
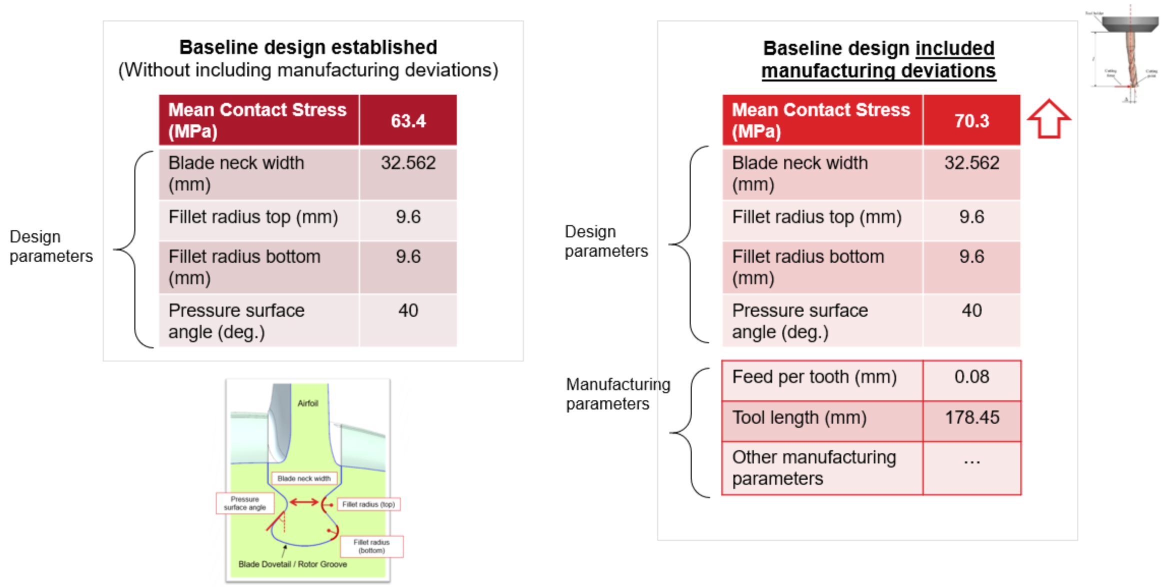


Figure 40: *Correlations between tool length, contact stresses, maximum pressure face deflection and length of pressure surface*

c) **Enriching Design Space Exploration with Manufacturing Information**

The following section discusses a demonstration case on how a designer / engineer can potentially make use of the design and manufacturing space exploration results. Given a baseline design was established, the performance metric (stress) is computed based on the as-designed CAD model. However, as the manufacturing deviation is being accounted for, the as-manufactured CAD model gives elevated stress value (**Figure 41**). By making use of DSE data, users can query design parameters that can satisfy given requirement after accounting for manufacturing deviations. For instance, by lowering blade neck width, the stress value is lowered in order to satisfy the original design requirement after including manufacturing deviations (**Figure 42**). On the other hand, in instances which design parameters have to be fixed, user can also query DSE data and identify manufacturing parameters that satisfy the requirement. In the example case here, by lowering the tool length, the contact stress is being reduced to lower value order to satisfy the original baseline requirement (**Figure 43**).



Baseline design established
(Without including manufacturing deviations)

Design parameters

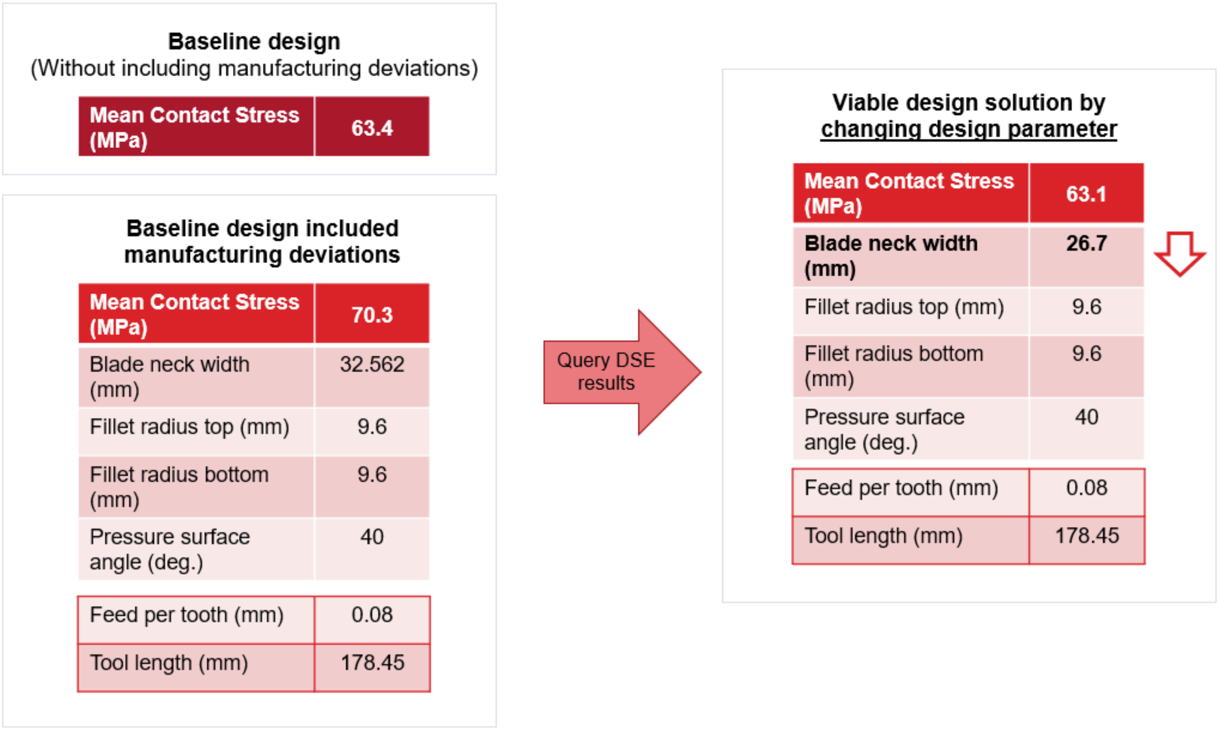
Mean Contact Stress (MPa)	63.4
Blade neck width (mm)	32.562
Fillet radius top (mm)	9.6
Fillet radius bottom (mm)	9.6
Pressure surface angle (deg.)	40

Baseline design included manufacturing deviations

Design parameters; Manufacturing parameters

Mean Contact Stress (MPa)	70.3
Blade neck width (mm)	32.562
Fillet radius top (mm)	9.6
Fillet radius bottom (mm)	9.6
Pressure surface angle (deg.)	40
Feed per tooth (mm)	0.08
Tool length (mm)	178.45
Other manufacturing parameters	…

***Figure 41**: Elevated stress after accounting for as-manufactured deviation in the CAD model*



Baseline design
(Without including manufacturing deviations)

Mean Contact Stress (MPa)	63.4

Baseline design included manufacturing deviations

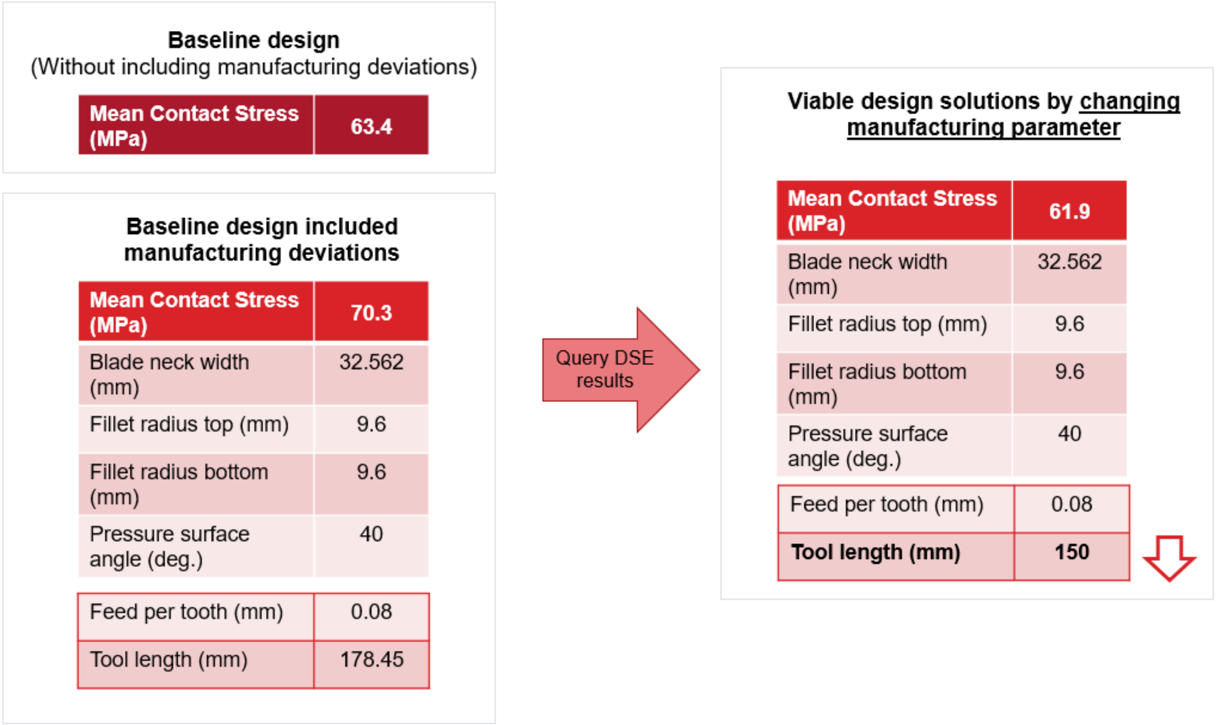
Mean Contact Stress (MPa)	70.3
Blade neck width (mm)	32.562
Fillet radius top (mm)	9.6
Fillet radius bottom (mm)	9.6
Pressure surface angle (deg.)	40
Feed per tooth (mm)	0.08
Tool length (mm)	178.45

Query DSE results

Viable design solution by changing design parameter

Mean Contact Stress (MPa)	63.1
Blade neck width (mm)	**26.7**
Fillet radius top (mm)	9.6
Fillet radius bottom (mm)	9.6
Pressure surface angle (deg.)	40
Feed per tooth (mm)	0.08
Tool length (mm)	178.45

***Figure 42**: Query DSE results for design parameters that satisfy performance requirement*



Baseline design
(Without including manufacturing deviations)

Mean Contact Stress (MPa)	63.4

Baseline design included manufacturing deviations

Mean Contact Stress (MPa)	70.3
Blade neck width (mm)	32.562
Fillet radius top (mm)	9.6
Fillet radius bottom (mm)	9.6
Pressure surface angle (deg.)	40
Feed per tooth (mm)	0.08
Tool length (mm)	178.45

Viable design solutions by changing manufacturing parameter

Mean Contact Stress (MPa)	61.9
Blade neck width (mm)	32.562
Fillet radius top (mm)	9.6
Fillet radius bottom (mm)	9.6
Pressure surface angle (deg.)	40
Feed per tooth (mm)	0.08
Tool length (mm)	**150**

Figure 43: *Query DSE results for manufacturing parameters that satisfy performance requirement*

Project Conclusions and Key Take-Aways

- Design space exploration integrates the assessment of design requirements and manufacturing capability, both of which are “in the loop” for each design iteration.
- Multiple design options are identified as opposed to single iterations
- Initial manufacturing parameters for given designs that satisfy profile tolerance requirements are provided; parameters are based currently on historical knowledge and experience
- Trade off analysis between design requirements, manufacturing capability and cost
- This process allows quicker design/manufacturing feedback and has the potential to significantly reduce new product development time and overall product cost.

Future Extensions

#	**Possible Extensions and future work for technical modules**
1	As-manufactured surface generation – inclusion of as-manufactured surface profile
2	As-manufactured surface generation - Other machine tool related errors, manufacturing process (other than milling)
3	Mating simulation – increase computational efficiency
4	Mating simulation – include influence of gravity
5	As design and as-manufactured functional performance evaluation – Improve accuracy of simulation by considering non-linear structural analysis, and mesh refinement studies
6	As design and as-manufactured functional performance evaluation – Include other types performance metrics that can influenced by as-manufactured surface deviation (e.g. flow leakage through the assembly, heat transfer, vibration)
7	Design space exploration framework – include multi-disciplinary KPI – e.g. design and manufacturing cost, tolerance analysis
8	Design space exploration framework – include material as a design variable in DSE
9	DSE queries – Other types of queries related to design and manufacturing space exploration: e.g. (I) decision making on manufacture in-house or procure from supplier, (ii) Trace the impact of requirement change / new requirement, (III) Leverage past DSE results to come up with new baseline design
10	Deployment of linked data framework to the Cloud
11	Visualization tool to visualize the best solutions among all parameters – e.g. 3D response surface

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Appendix B: References

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