# MAE 598: Design Optimization

# Project 2. Design Optimization of a Brake Disk

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## Problem Statement

The goal for this project is to build a brake disc for emergency braking scenarios with minimal volume. Four subsystems required are. 1. Minimize the maximum volume. 2. Maximize the natural frequency of the brake disc. 3. Minimize the maximum temperature in the brake disc. 4. Minimize the maximum stress in the brake disc. The simulation is performed on Ansys.

## Model Setup

A brake disk part model is provided by Dr. Yi Ren for the course of MAE 598: Design Optimization for the purpose of Project 2: Brake disk optimization. The brake file (.agdb) is used as the Input to ANSYS workbench which is later used by different analysis modules. The model setup is shown in Figure 1. The initial values are 125mm, 75mm and 25mm respectively.

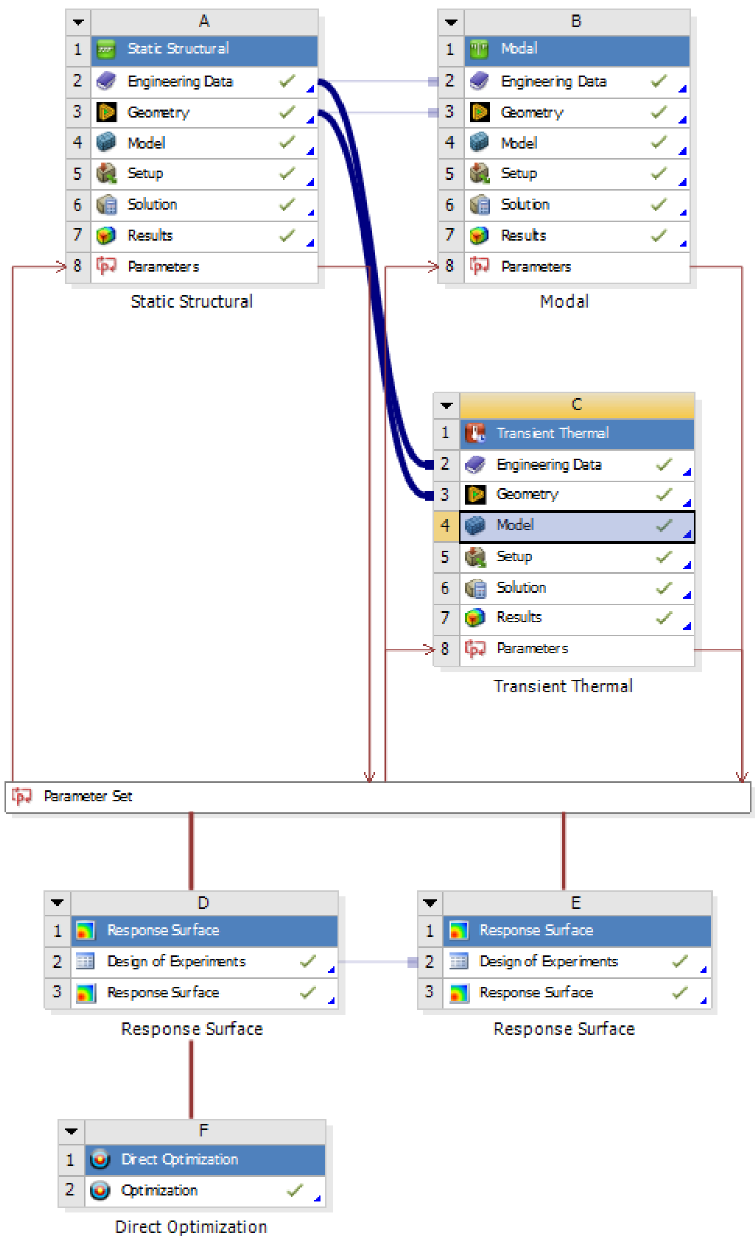


**Figure 1:** Model Setup

## Static mechanical analysis

In this model, we mesh the disc with Tetrahedrons. the inner faces of the brake pads and set element size to 3 mm to better analyze the high stress concentration at this part. The brick disk is set to be rotated at 250 rad/s in y direction. The revolute joint is set at inner diameter. Pressure is applied on both outer brake pad faces with value equals to 1.0495*10^7pa. There is a frictional contact between disc and pads with friction coefficient 0.22. The displacement of the disc is fix in x and z direction.

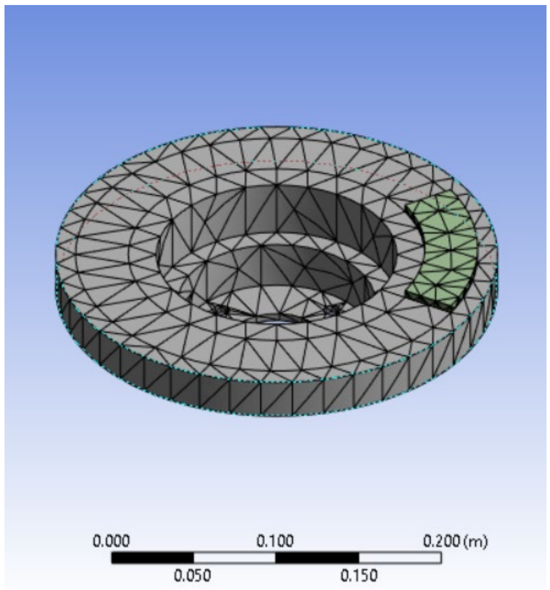


**Figure 2:** Mesh

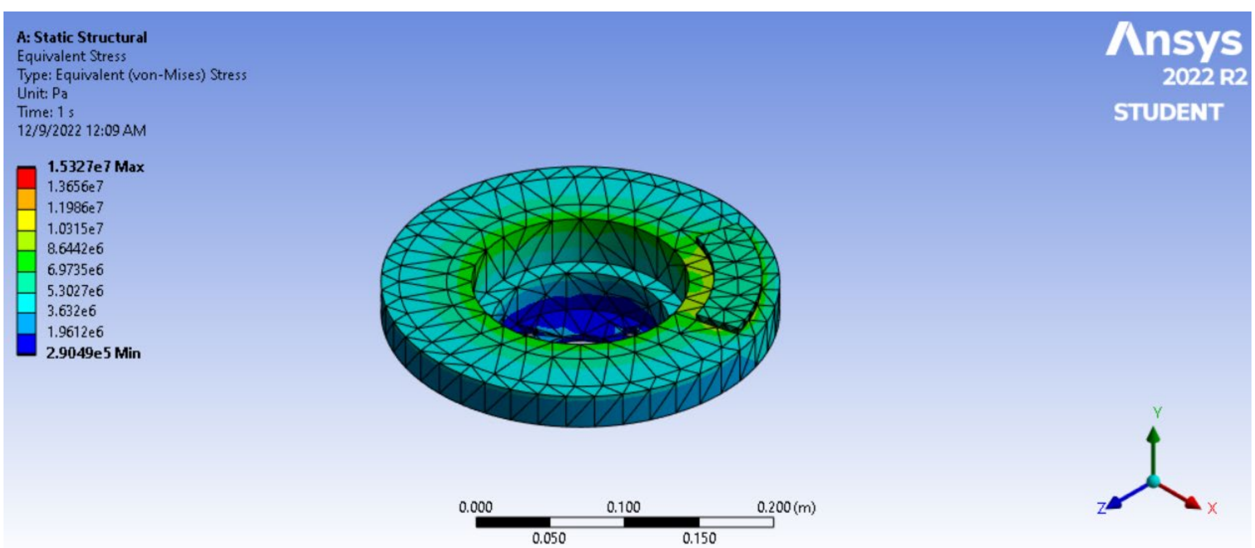


**Figure 3:** Distribution of the Von Mises stress

## Modal analysis

This part we suppress the Brake pads to find the natural frequency of the brake disc only. The Max Modes is set to 10.

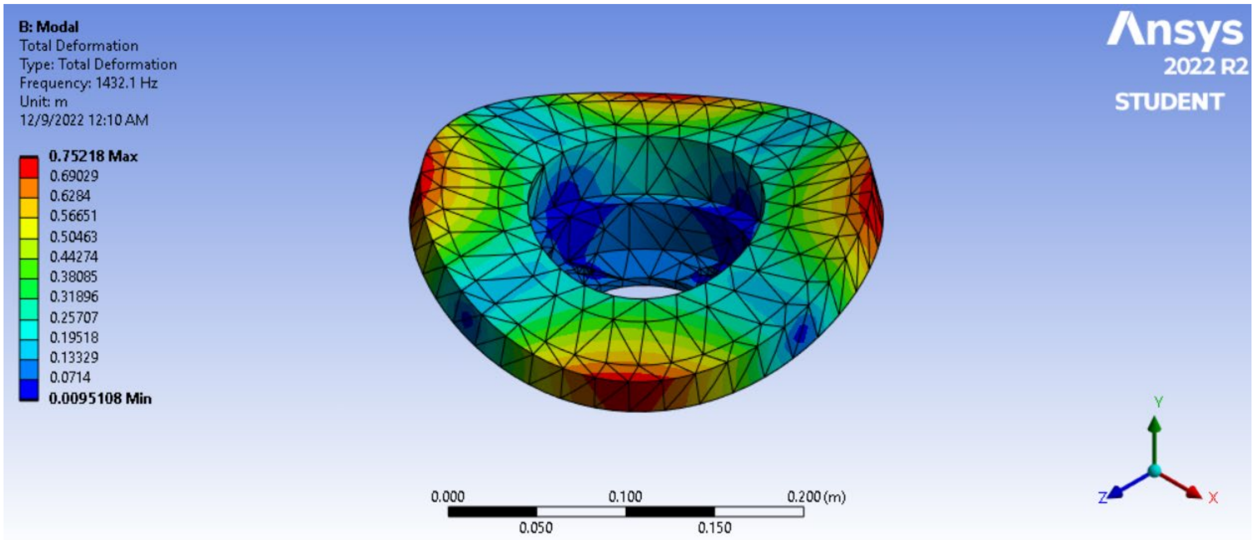


**Figure 4:** Deformation of the 7th vibration mode

## Transient thermal analysis

The same geometry and materials are adopted and the two brake pads are suppressed from the simulation. Convection boundary conditions are applied to all the faces of the geometry, with factor set as 5 W/m2. Heat flux of 1500 kW/m2 is applied to the surface of main body contacting with the pads.

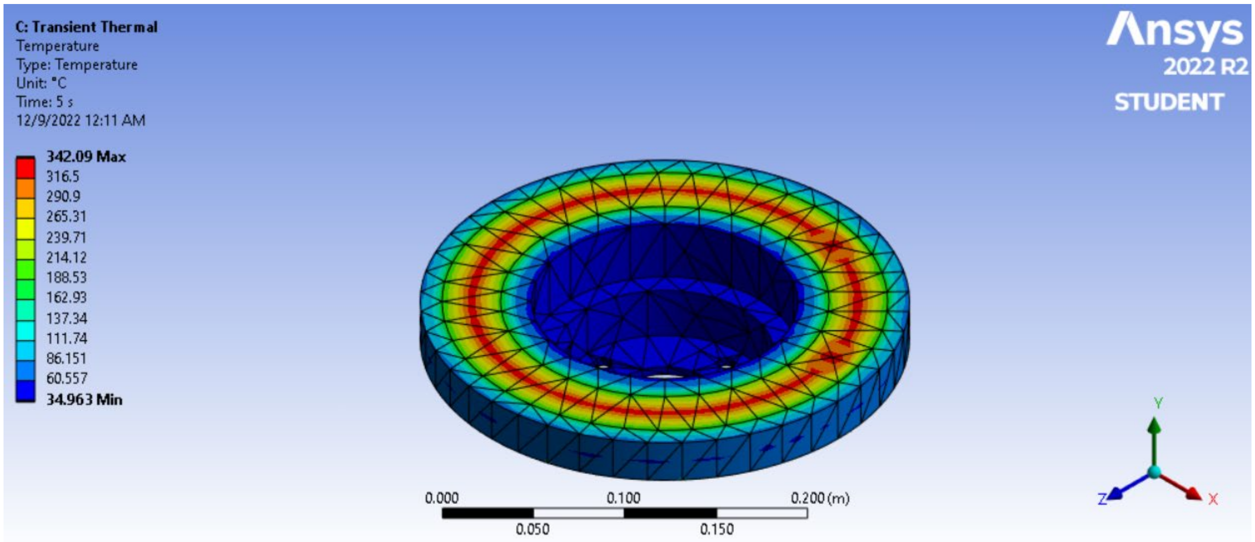


**Figure 5:** Temperature distribution of the Initial design

## Design of Experiment

To conduct the tests, the Latin Hypercube Sampling (LHS) method is used. The input variables' numbers are chosen at random from a specified range, and 20 points are chosen at random. The outcomes for the DOE are shown in Figure 7.

| | A | B |
|---|---|---|
| 1 | Property | Value |
| 2 | Design Points | |
| 3 | Preserve Design Points After DX Run | |
| 4 | Failed Design Points Management | |
| 5 | Number of Retries | 0 |
| 6 | Design of Experiments | |
| 7 | Design of Experiments Type | Latin Hypercube Sampling Design |
| 8 | Samples Type | User-Defined Samples |
| 9 | Random Generator Seed | 0 |
| 10 | Number of Samples | 20 |

**Figure 6:** DOE

| Design variables (mm) | Lower bound(mm) | Upper bound(mm) |
|---|---|---|
| Inner diameter | 70 | 82 |
| Outer diameter | 125 | 140 |
| Thickness | 22.5 | 27.5 |

**Table 1:** Range for parameters

Table of Outline A14: Design Points of Design of Experiments

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | Name | P1 - rotor_thickness (mm) | P2 - rotor_OD (mm) | P3 - rotor_ID (mm) | P6 - Temperature Maximum (C) | P7 - Equivalent Stress Maximum (Pa) | P8 - Total Deformation Reported Frequency (Hz) | P9 - Volume Maximum (m^3) |
| 2 | 1 | 25.125 | 128.38 | 78.1 | 343.7 | 1.1666E+07 | 1519.4 | 3.2314E-06 |
| 3 | 2 | 26.125 | 135.13 | 71.5 | 339.05 | 1.1539E+07 | 1482.7 | 3.5736E-06 |
| 4 | 3 | 22.625 | 135.88 | 73.3 | 348.57 | 1.1571E+07 | 1411.1 | 2.5455E-06 |
| 5 | 4 | 25.625 | 125.38 | 72.7 | 339.21 | 1.2037E+07 | 1654.6 | 2.0957E-06 |
| 6 | 5 | 23.125 | 130.63 | 80.5 | 350.71 | 1.2208E+07 | 1415.8 | 2.6675E-06 |
| 7 | 6 | 27.375 | 131.38 | 78.7 | 339.16 | 1.2127E+07 | 1494.1 | 3.0427E-06 |
| 8 | 7 | 25.375 | 134.38 | 81.1 | 344.21 | 1.2031E+07 | 1393.6 | 3.8555E-06 |
| 9 | 8 | 27.125 | 132.88 | 75.1 | 339.85 | 1.2079E+07 | 1511.7 | 3.084E-06 |
| 10 | 9 | 24.125 | 138.88 | 70.3 | 342.97 | 1.1407E+07 | 1380.3 | 3.0114E-06 |
| 11 | 10 | 23.875 | 126.13 | 72.1 | 343.19 | 1.1679E+07 | 1620.8 | 2.1141E-06 |
| 12 | 11 | 24.625 | 132.13 | 70.9 | 343.92 | 1.1563E+07 | 1527.6 | 3.4364E-06 |
| 13 | 12 | 23.625 | 133.63 | 79.3 | 345.92 | 1.1761E+07 | 1401.5 | 3.5653E-06 |
| 14 | 13 | 24.875 | 129.88 | 81.7 | 344.12 | 1.2463E+07 | 1425.3 | 3.2469E-06 |
| 15 | 14 | 26.375 | 136.63 | 75.7 | 338.13 | 1.1612E+07 | 1437.6 | 3.3425E-06 |
| 16 | 15 | 24.375 | 126.88 | 73.9 | 341.98 | 1.1601E+07 | 1590.2 | 2.7533E-06 |
| 17 | 16 | 26.875 | 127.63 | 76.9 | 337.57 | 1.1982E+07 | 1576.6 | 4.3742E-06 |
| 18 | 17 | 26.625 | 139.63 | 77.5 | 336.77 | 1.1894E+07 | 1374.6 | 4.3194E-06 |
| 19 | 18 | 25.875 | 137.38 | 76.3 | 338.43 | 1.1488E+07 | 1409.8 | 4.1045E-06 |
| 20 | 19 | 23.375 | 129.13 | 74.5 | 346.59 | 1.1682E+07 | 1538.5 | 2.7027E-06 |
| 21 | 20 | 22.875 | 138.13 | 79.9 | 347.7 | 1.1862E+07 | 1321 | 3.057E-06 |

**Figure 7:** DOE Results

## Response surface

For each input and output, a reaction surface is created. The link between the input parameters and the responses is fitted using neural networks. To gauge the precision of the response surface, four verification points are used.

| | A | B |
|---|---|---|
| 1 | Property | Value |
| 2 | ⊟ Design Points | |
| 3 | Preserve Design Points After DX Run | ☐ |
| 4 | ⊟ Failed Design Points Management | |
| 5 | Number of Retries | 0 |
| 6 | ⊟ Meta Model | |
| 7 | Response Surface Type | Neural Network |
| 8 | Number of Cells | 5 |
| 9 | ⊟ Refinement | |
| 10 | Refinement Type | Manual |
| 11 | ⊟ Verification Points | |
| 12 | Generate Verification Points | ☑ |
| 13 | Number of Verification Points | 4 |
| 14 | ⊟ Design Point Report | |

**Figure 8:** Response Surface

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | | P6 - Temperature Maximum | P7 - Equivalent Stress Maximum | P8 - Total Deformation Reported Frequency | P9 - Volume Maximum |
| 2 | ⊟ Coefficient of Determination (Best Value = 1) | | | | |
| 3 | Learning Points | 0.93423 | 0.78217 | 0.98004 | 0.43092 |
| 4 | ⊟ Root Mean Square Error (Best Value = 0) | | | | |
| 5 | Learning Points | 0.99869 | 1.2756E+05 | 12.564 | 4.7362E-07 |
| 6 | Verification Points | 1.9163 | 1.4193E+05 | 48.228 | 8.6054E-07 |
| 7 | ⊟ Relative Maximum Absolute Error (Best Value = 0%) | | | | |
| 8 | Learning Points | 61.734 | 115.51 | 26.946 | 170.73 |
| 9 | Verification Points | 68.071 | 66.088 | 77.992 | 236.04 |
| 10 | ⊟ Relative Average Absolute Error (Best Value = 0%) | | | | |
| 11 | Learning Points | 20.08 | 33.299 | 11.685 | 60.852 |
| 12 | Verification Points | 42.831 | 48.858 | 46.313 | 88.397 |

**Figure 9:** Goodness of Fit

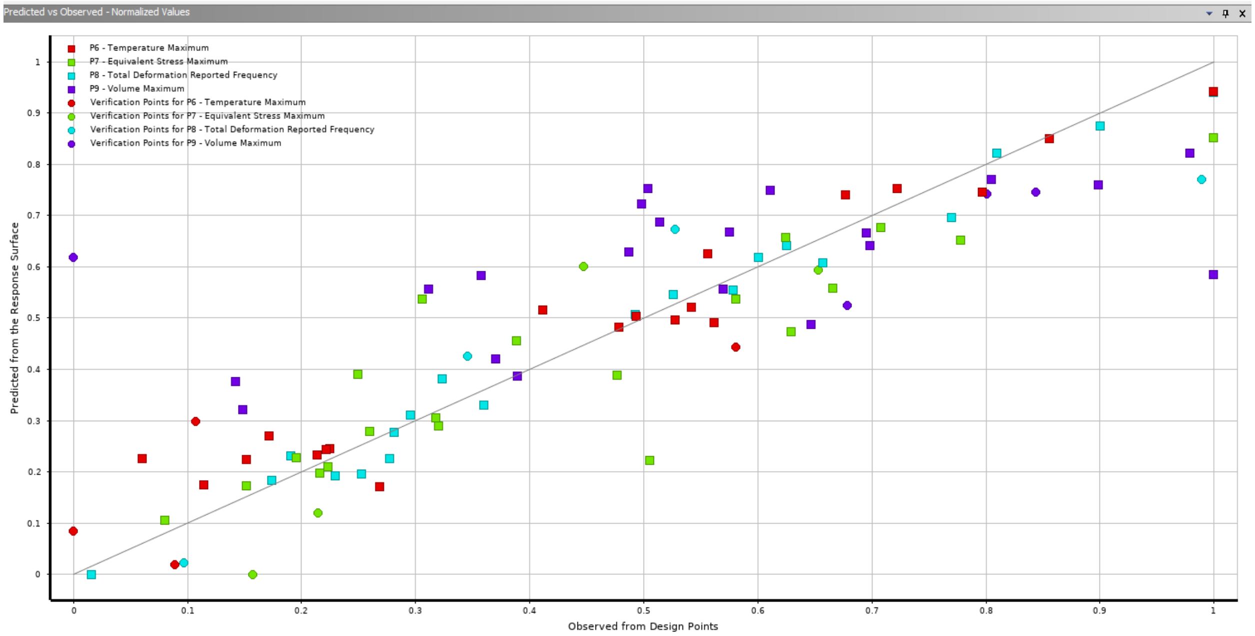


**Figure 10:** Predicted Values V/S Observed Values

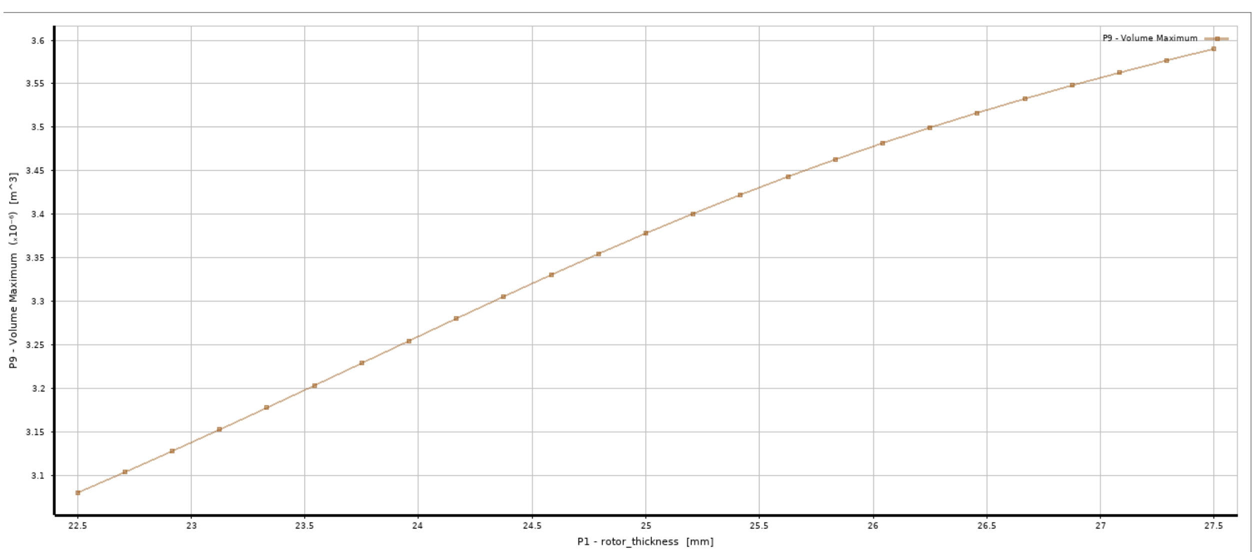


**Figure 11:** Response Chart (Max Vol V/S Thickness)

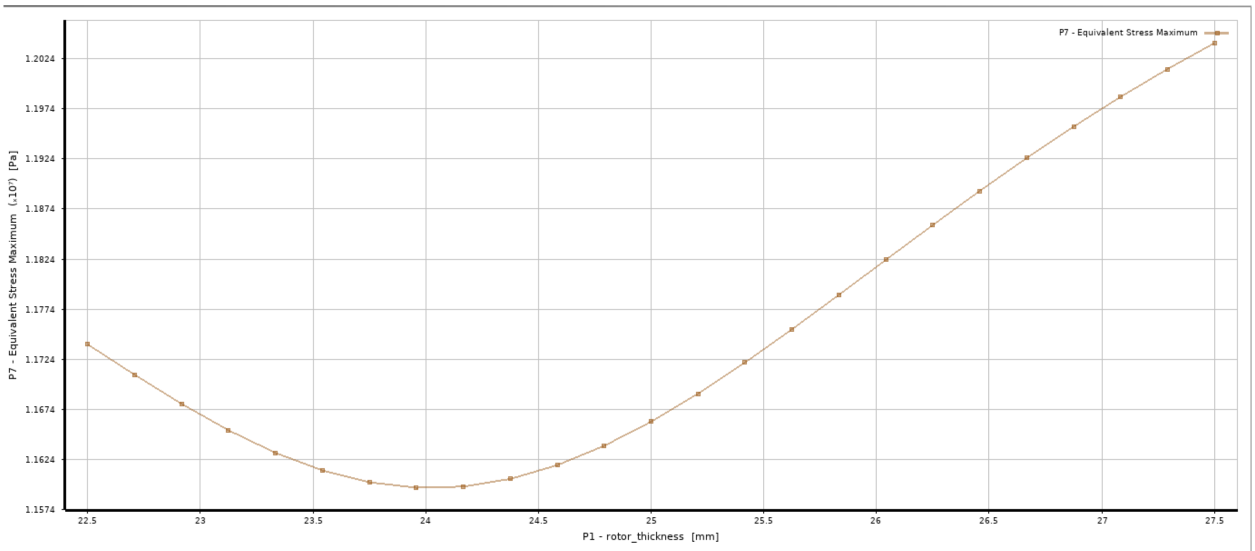


**Figure 12:** Response Chart (Max Von-Mises Stress V/S Thickness)

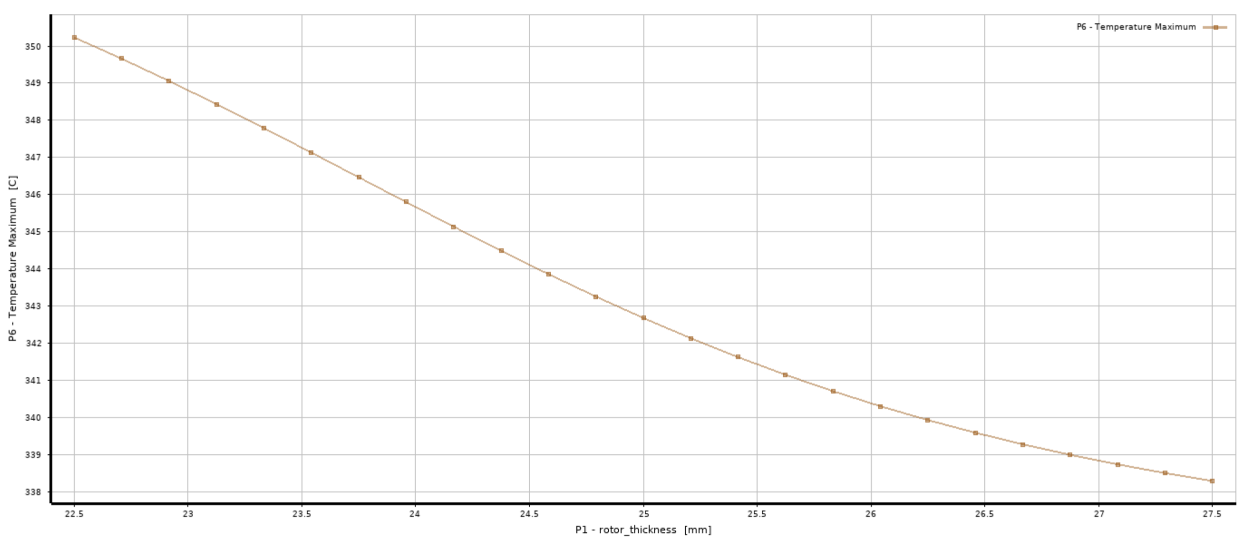


**Figure 13:** Response Chart (Max Temperature V/S Thickness)

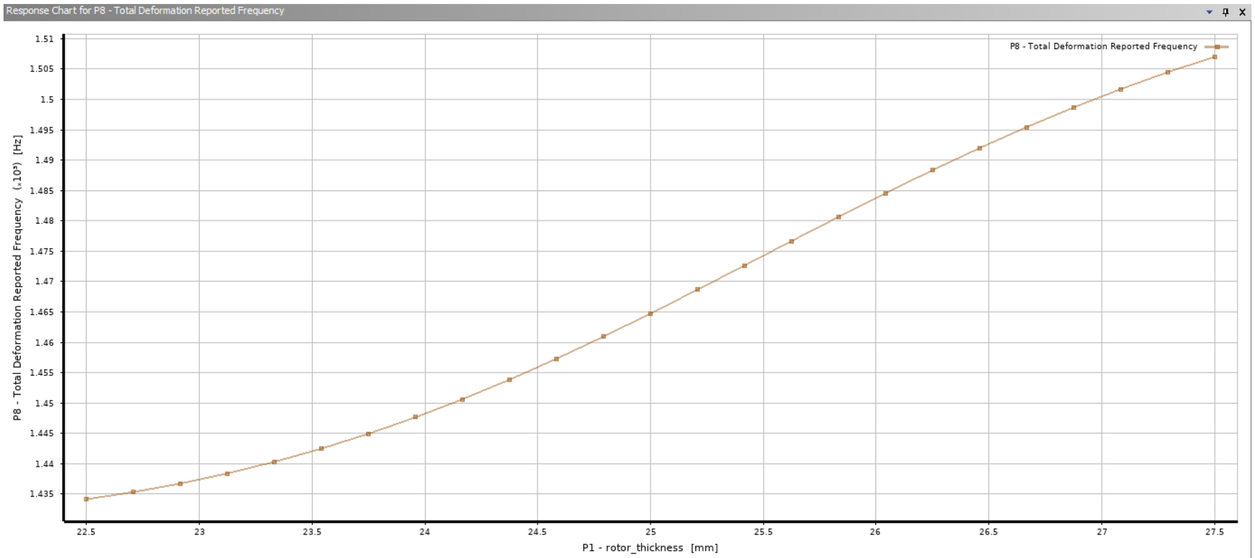


**Figure 14:** Response Chart (Frequency of Vibration V/S Thickness)

## Sensitivity

The ANSYS can calculate the sensitivity between design factors and responses, and it is plotted below. According to the findings of the sensitivity analysis, the maximum stress is most positively impacted by the rotor thickness, and increasing the inner and outer diameters would also raise the stress value. The brake disk's thickness affects temperature the most, and it can be increased to lower temperature. The volume of the disk will decrease with decreasing thickness and outer diameter and increase with decreasing inner diameter.

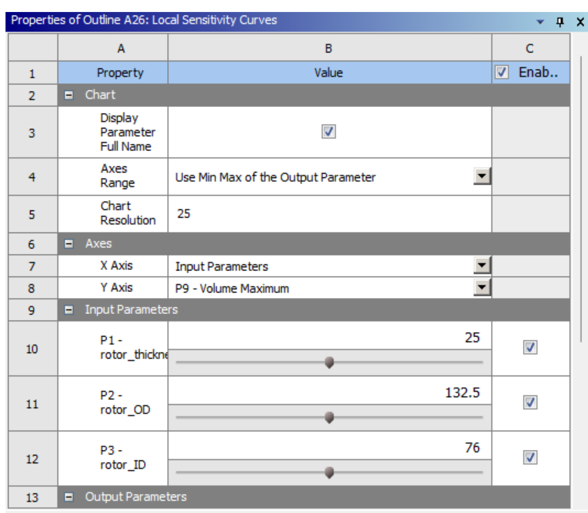


**Figure 15:** Properties of Sensitivity Analysis

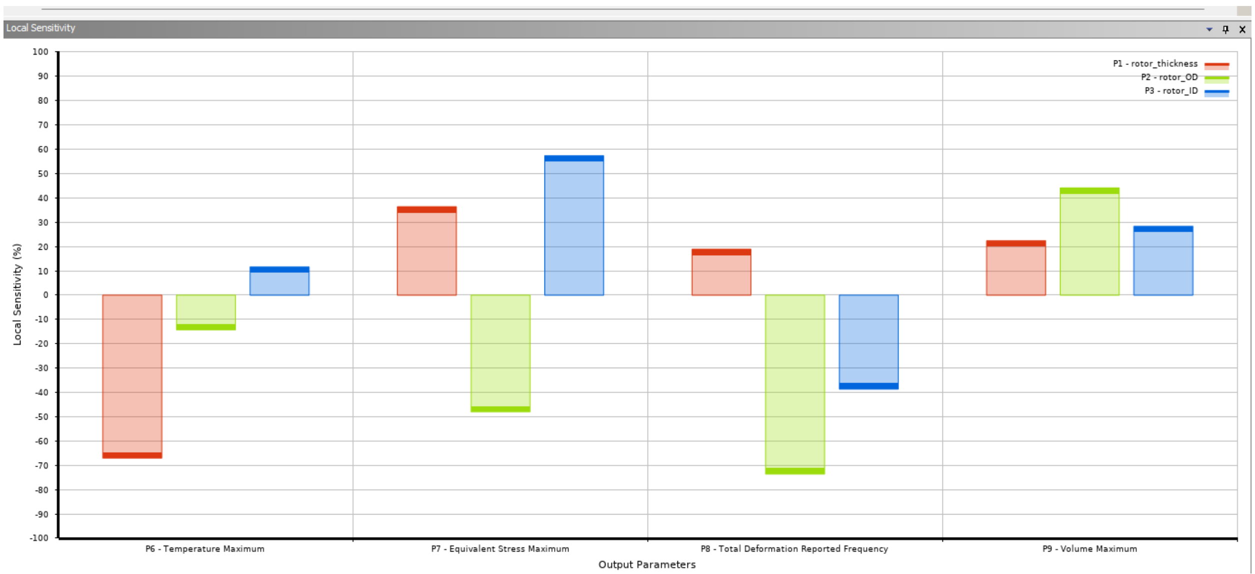


**Figure 16:** Local Sensitivity

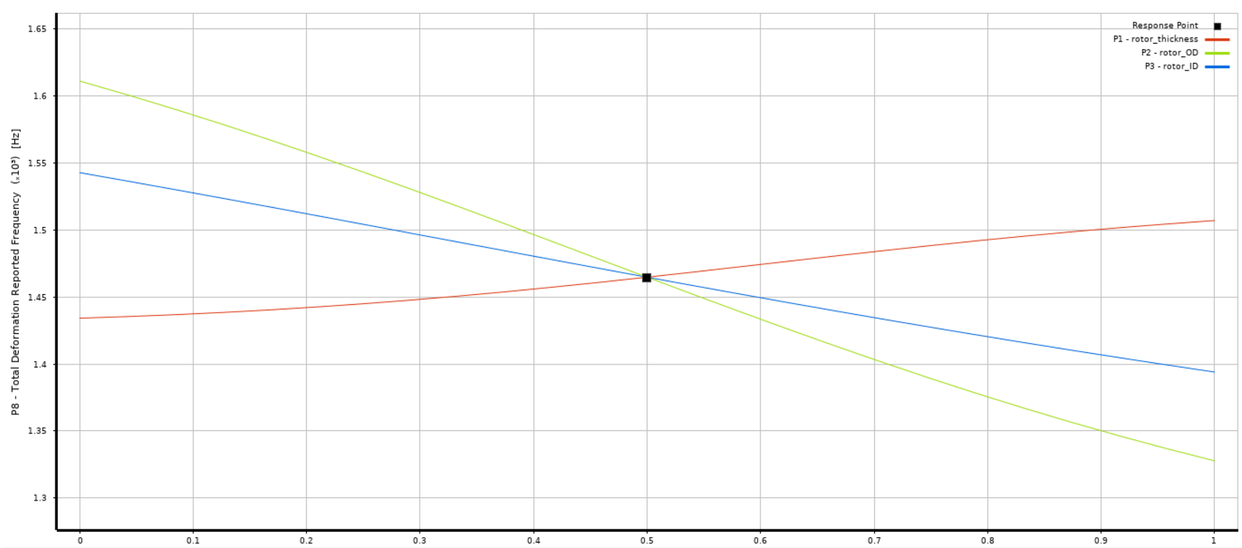


**Figure 15:** Local Sensitivity curve for Vibrational Frequency

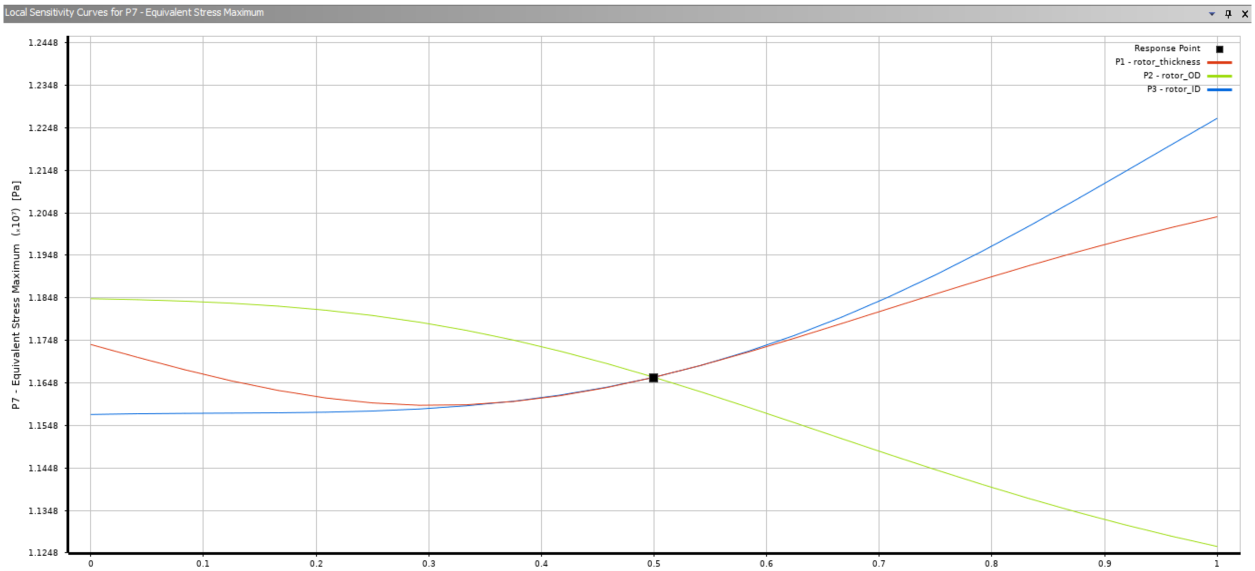


**Figure 15:** Local Sensitivity curve for Von-Mises Stress

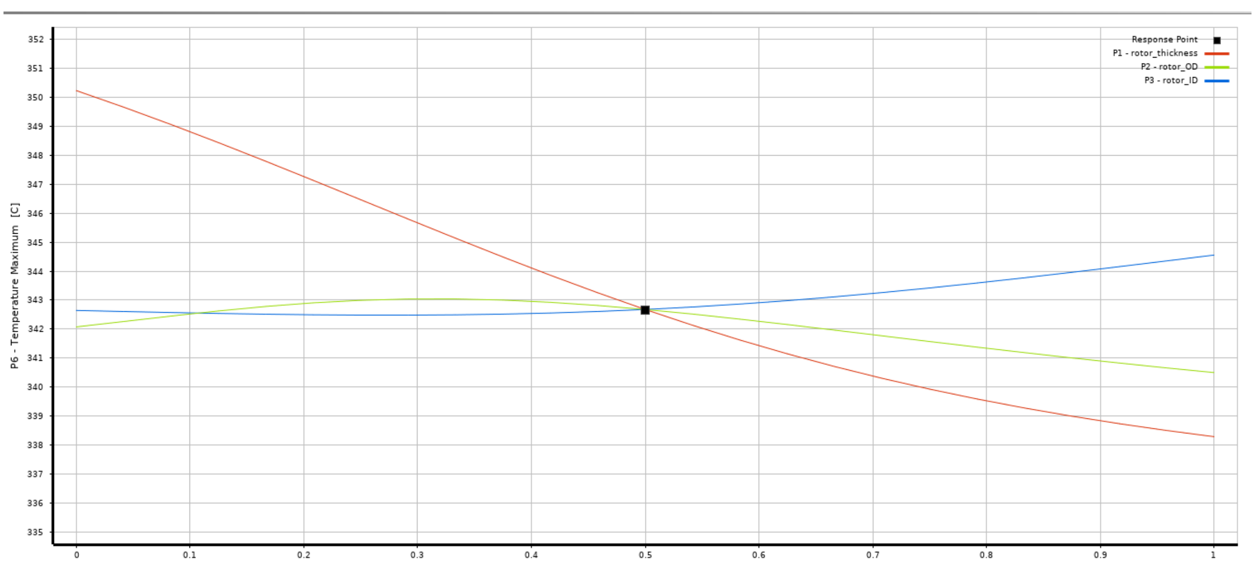


**Figure 15:** Local Sensitivity curve for Max Temperature

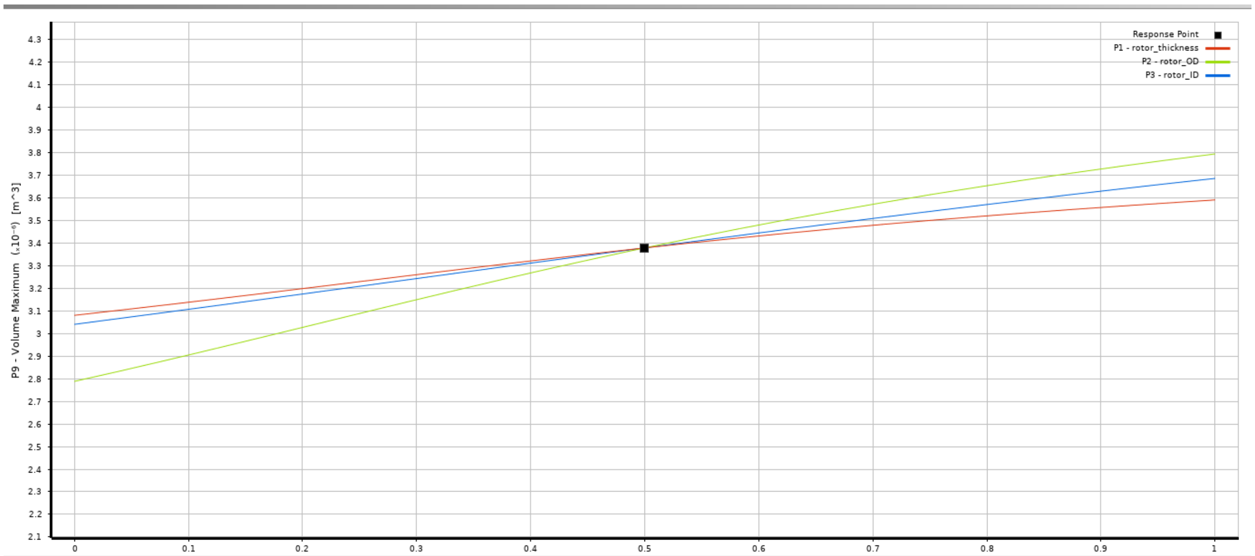


**Figure 15:** Local Sensitivity curve for Max Volume

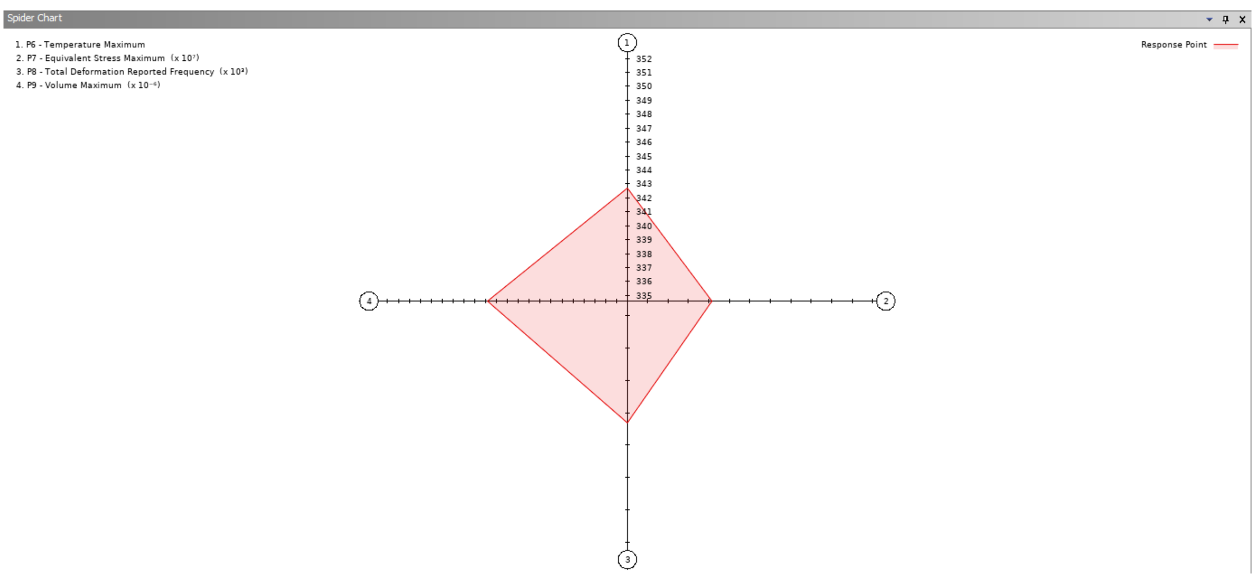


**Figure 16:** Spider Plot

## Optimization

The primary goal of this project was to improve the brake pad that was already in use by minimizing volume, stress, temperature, and maximizing frequency. This design performs better in terms of temperature reduction and stress release than the one offered by Professor Yi Ren. This model provides an explanation for the final design based on engineering parameters and response surfaces. If we raise the thickness, the temperature will be a little bit lower, and the frequency will be a little bit different. This optimization effort will also heavily rely on changing the lower and upper boundaries. The Multi-objective Genetic Algorithm (MOGA) is utilized to identify the top design candidates because this design has numerous objectives. As was already established, the goal of the optimization is to maximize frequency while minimizing volume, stress, and temperature. Each response receives a default significance. The top design contenders are displayed below. Compared with the initial design, the optimized versions have superior performance on stress alleviation, greater frequency, and better temperature regulation although, the reduction of volume is not much.

| | A | B |
|---|---|---|
| 1 | Property | Value |
| 6 | Optimization | |
| 7 | Method Selection | Manual |
| 8 | Method Name | MOGA |
| 9 | Estimated Number of Design Points | 96 |
| 10 | Tolerance Settings | ☑ |
| 11 | Number of Initial Samples | 20 |
| 12 | Number of Samples Per Iteration | 4 |
| 13 | Maximum Allowable Pareto Percentage | 70 |
| 14 | Convergence Stability Percentage | 2 |
| 15 | Maximum Number of Iterations | 20 |
| 16 | Maximum Number of Candidates | 3 |

**Figure 17:** Optimization Properties

| Table of Schematic F2: Optimization | | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 1 | ⊟ Optimization Study | | | |
| 2 | Minimize P6 | Goal, Minimize P6 (Default importance) | | |
| 3 | Minimize P7 | Goal, Minimize P7 (Default importance) | | |
| 4 | Maximize P8 | Goal, Maximize P8 (Default importance) | | |
| 5 | Minimize P9 | Goal, Minimize P9 (Default importance) | | |
| 6 | ⊟ Optimization Method | | | |
| 7 | MOGA | The MOGA method (Multi-Objective Genetic Algorithm) is a variant of the popular NSGA-II (Non-dominated Sorted Genetic Algorithm-II) based on controlled elitism concepts. It supports multiple objectives and constraints and aims at finding the global optimum. | | |
| 8 | Configuration | Generate 20 samples initially, 4 samples per iteration and find 3 candidates in a maximum of 20 iterations. | | |
| 9 | Status | Converged after 38 evaluations. | | |
| 10 | ⊟ Candidate Points | | | |
| 11 | | Candidate Point 1 | Candidate Point 2 | Candidate Point 3 |
| 12 | P1 - rotor_thickness (mm) | 22.659 | 22.659 | 22.659 |
| 13 | P2 - rotor_OD (mm) | 125.4 | 125.4 | 125.4 |
| 14 | P3 - rotor_ID (mm) | 75.767 | 75.767 | 75.767 |
| 15 | P6 - Temperature Maximum (C) | 346.9 | 346.9 | 349.35 |
| 16 | P7 - Equivalent Stress Maximum (Pa) | 1.0979E+07 | 1.0979E+07 | 1.1134E+07 |
| 17 | P8 - Total Deformation Reported Frequency (Hz) | 1560.3 | 1560.3 | 1560.1 |
| 18 | P9 - Volume Maximum (m^3) | 1.6195E-06 | 1.6195E-06 | 1.6914E-06 |

**Figure 18:** Optimized Values

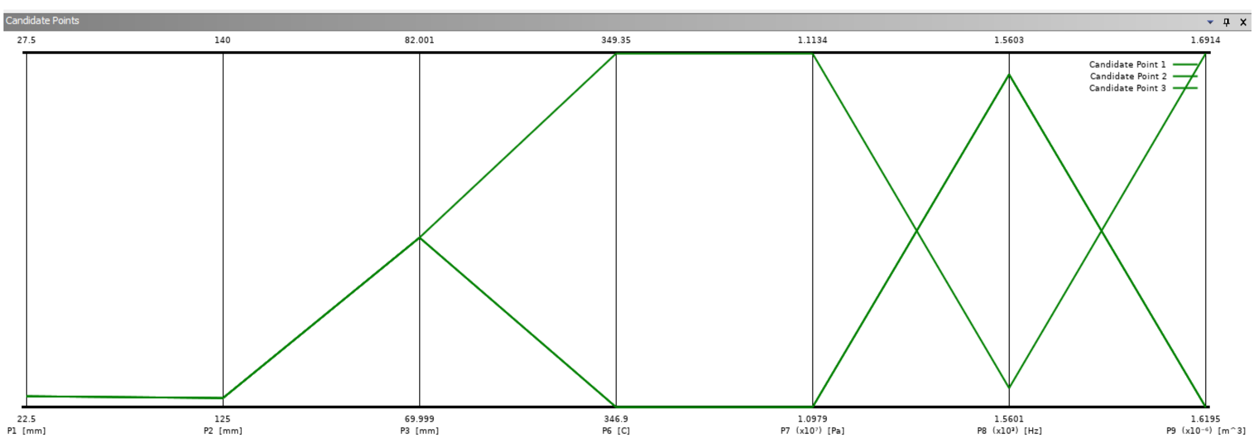


**Figure 19:** Candidate Points