Improving Quality Audits for GE Energy Airfoils

Senior Design Final Presentation

Spring 2009
April 29, 2009

Michael Chan
Tareq Dowla
Myles Lefkovitz
Tanzil Manawar
Lance Sun
Chiu Tong Tsang

Advisor: Shabbir Ahmed
GE Contact 1: Doug Heend, Black Belt
GE Contact 2: Bryan Graffagnini, Quality Manager

Disclaimer: This work has not been officially sanctioned by The Georgia Institute of Technology or General Electric.
Background

GE Energy Airfoils produces airfoils for use in turbines. The plant is located in Duluth, GA.

- 4600 airfoils/week
- ~16 types per turbine
- 1/1000th inch tolerance
- Shape and texture consistency
Manufacturing Layout

Forges

Coordinate Measuring Machine (CMM)
### Problems

| Lack of manager visibility | • Dashboard system  
|                           | • Detect trends and variation early |
| Excessive inspection time | • Correlation study  
|                           | • Eliminate redundant checkpoints |
| Inaccurate In-process tolerance levels | • Linear regression  
|                                     | • Prevent loss of resources |

**Potential Savings:** $830,000
Problem 1: Lack of quality visibility in the process

There is poor visibility when determining if there are airfoils out of specification.

Unable to identify machine shift

Unable to identify high variation processes

Consecutive Defects

Lack of Quality Visibility

In 2008, this lack of visibility resulted in $200,000 in defect costs.
Problem 1: Methodology

Updating tools in Microsoft Access to increase visibility and improve quality

- Automatically aggregate CMM data
- Detect out-of-control processes (using z-scores)
- Visualize via control charts
Problem 1: Control Charts - X-bar and Range

Xbar Control Chart

Out of Control

Measurement

0.176
0.171
0.166
0.161
0.156

1 4 7 10 13 16 19 22 25 28 31 34 37

Blade Number

Sample Averages
UCL
LCL
Nominal
Mean
Problem 2: Excessive Inspection Time

~25 minutes on average to CMM an airfoil

- 3000 airfoils/week measured
- 1250 hours/week of CMM time

- Shortage cost of airfoils: $150,000/year
- Cost of CMM machine: $150,000
Problem 2: Methodology

- Reduce cycle time by reducing number of sections inspected
- Correlation between sections implies redundancy
- Remove redundant sections without losing too much detection power
Problem 2: Methodology

- Linear model estimates measurements of removed sections from those of retained sections
- Loss of detection power (Index) is calculated from the linear model as a function of retained sections
- Find optimal set of retained sections to minimize Index
### Problem 2: Methodology

<table>
<thead>
<tr>
<th># Retained</th>
<th>Retained Sections</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.00%</td>
</tr>
<tr>
<td>12</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.03%</td>
</tr>
<tr>
<td>11</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.06%</td>
</tr>
<tr>
<td>10</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.11%</td>
</tr>
<tr>
<td>9</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.18%</td>
</tr>
<tr>
<td>8</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.30%</td>
</tr>
<tr>
<td>7</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.45%</td>
</tr>
<tr>
<td>6</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.63%</td>
</tr>
<tr>
<td>5</td>
<td>CDEFGHIJKLMNOPR</td>
<td>0.82%</td>
</tr>
<tr>
<td>4</td>
<td>CDEFGHIJKLMNOPR</td>
<td>1.46%</td>
</tr>
<tr>
<td>3</td>
<td>CDEFGHIJKLMNOPR</td>
<td>2.62%</td>
</tr>
<tr>
<td>2</td>
<td>CDEFGHIJKLMNOPR</td>
<td>6.90%</td>
</tr>
<tr>
<td>1</td>
<td>CDEFGHIJKLMNOPR</td>
<td>16.78%</td>
</tr>
<tr>
<td>0</td>
<td>CDEFGHIJKLMNOPR</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
Problem 2: Results

Retain

- 4 sections: C, H, N, R

Index Value

- 1.46% loss of detection power
- Detect 98.54% of all defects

CMM inspection cycle time

- 70% reduction
Problem 3: Inaccurate In-Process Tolerance Levels

Potential defective airfoils passing quality checks in process

Wasted work on defective airfoils

In 2008, this lack of process understanding resulted in $180,000 spent on making parts that would eventually be found defective.
Problem 3: Correlation Study

- Each In-Process feature is estimated from all final features
- Identify pairs with correlation of 70% or higher
- Perform correlation on every pair of features

<table>
<thead>
<tr>
<th>Final Features</th>
<th>After Machining CC Cont Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final CC Cont Max</td>
<td>90%</td>
</tr>
<tr>
<td>Final CC Cont Min</td>
<td>70%</td>
</tr>
<tr>
<td>Final Centroid CC-CX</td>
<td>-14%</td>
</tr>
<tr>
<td>Final Centroid LE-TE</td>
<td>-9%</td>
</tr>
<tr>
<td>Final Chord</td>
<td>30%</td>
</tr>
<tr>
<td>Final CX Cont Max</td>
<td>74%</td>
</tr>
<tr>
<td>Final CX Cont Min</td>
<td>65%</td>
</tr>
<tr>
<td>Final LE Cont Max</td>
<td>59%</td>
</tr>
<tr>
<td>Final LE Cont Min</td>
<td>17%</td>
</tr>
<tr>
<td>Final LE Drop</td>
<td>-21%</td>
</tr>
<tr>
<td>Final LE Thickness</td>
<td>73%</td>
</tr>
<tr>
<td>Final Max Thickness</td>
<td>89%</td>
</tr>
<tr>
<td>Final TE Cont Max</td>
<td>59%</td>
</tr>
<tr>
<td>Final TE Cont Min</td>
<td>54%</td>
</tr>
<tr>
<td>Final TE Thickness</td>
<td>85%</td>
</tr>
<tr>
<td>Final Warp</td>
<td>-3%</td>
</tr>
</tbody>
</table>
Problem 3: Methodology

Final (Known) Tolerance Levels → Linear Regression → In-Process (Predicted) Tolerance Levels

Final CC Cont Max (Known) vs. After Machining CC Cont Max (Predicted)

\[ y = 0.9177x - 0.0006 \]

\[ R^2 = 0.8382 \]
### Problem 3: Results

#### Tolerance level for feature After Machining CC Cont Max

<table>
<thead>
<tr>
<th>Feature</th>
<th>Lower Tolerance</th>
<th>Upper Tolerance</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final CC Cont Max</td>
<td>-0.0086</td>
<td>0.0105</td>
<td>90%</td>
</tr>
<tr>
<td>Final CC Cont Min</td>
<td>-0.0033</td>
<td>0.0084</td>
<td>70%</td>
</tr>
<tr>
<td>Final CX Cont Max</td>
<td>-0.0052</td>
<td>0.0075</td>
<td>74%</td>
</tr>
<tr>
<td>Final LE Thickness</td>
<td>-0.0005</td>
<td>0.0038</td>
<td>73%</td>
</tr>
<tr>
<td>Final Max Thickness</td>
<td>-0.0077</td>
<td>0.0114</td>
<td>89%</td>
</tr>
<tr>
<td>Final TE Thickness</td>
<td>-0.0042</td>
<td>0.0067</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Expected Tolerance</strong></td>
<td><strong>-0.0071</strong></td>
<td><strong>0.0097</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Conservative Tolerance</strong></td>
<td><strong>-0.0039</strong></td>
<td><strong>0.0073</strong></td>
<td></td>
</tr>
</tbody>
</table>
Potential Value

Dashboard

• Prevention of consecutive defects: $200,000 savings in 2008

CMM inspection section removal

• Removing an average of 9 CMM inspection sections per airfoil type: $300,000 savings (cost of 2 additional CMM machines)
• Producing one additional set (all airfoils on a turbine): $150,000 savings in purchasing costs annually

More accurate tolerance levels

• $180,000 savings in 2008 (provides better understanding of how the manufacturing process affects the airfoil)

Total savings: $830,000
Appendix A: Problem 1

- Western Electric rules

Graph from: (http://www.micquality.com/six_sigma_glossary/western_electric.htm)
Appendix B: Problem 1

• Z-Score Calculations

\[ z = \min\left(\frac{Tol_{Upper} - \bar{x}}{\sigma}, \frac{\bar{x} - Tol_{Lower}}{\sigma}\right) \]

\[ z = \min\left(\frac{0.1772 - 0.166814}{0.001881}, \frac{0.166814 - 0.1572}{0.001881}\right) = \min(5.52, 5.11) = 5.11 \]
Appendix C – Problem 2: Correlation Formulas

- $K_{tot}$ – Covariance matrix of all measurements.
- $K_{ret}$ – Covariance matrix of retained measurements (submatrix of $K_{tot}$).
- $K_{ret/tot}$ – Cross-covariance matrix between retained and all measurements (submatrix of $K_{tot}$).
- $K_{spec}$ – Diagonal matrix based on the upper and lower specification tolerances of all measurements, where each element $i$ is defined as:
  
  $K_{spec(i)} = [(\text{Upper bound for measurement } i) - (\text{Lower bound for measurement } i)]^2$

$$M_2'' = K_{spec}^{-1/2} [K_{tot} - K_{ret/tot}^T K_{ret/tot}^{-1} K_{ret/tot}] K_{spec}^{-1/2}$$

$$Index_2'' = \frac{\text{trace}(M_2'')}{K_{spec}^{-1/2} K_{tot} K_{spec}^{-1/2}}$$
Appendix D – Problem 2: Correlation Graphs

Index$^2$ - TE THK .080 CE

Index$^2$ - CHORD

Index$^2$ - WARP

Index$^2$ - CENTROID LE-TE
Appendix D – Problem 2: Correlation Graphs

Index$^2$ - CENTROID CC-CX

Index$^2$ - CX CONT MIN

Index$^2$ - CX CONT MAX

Index$^2$ - CC CONT MIN
Appendix D – Problem 2: Correlation Graphs

Index''2 - CC CONT MAX

Index''2 - LE CONT MIN

Index''2 - LE CONT MAX

Index''2 - TE CONT MIN
Appendix D – Problem 2: Correlation Graphs

Index"2 - TE CONT MAX

Number of Sections Retained

% Loss of Information

100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%

13 12 11 10 9 8 7 6 5 4 3 2 1 0
Appendix E: Problem 3

• **Step 1: Linear Regression**

\[ y = \alpha x + \beta + \varepsilon \]

\[ \varepsilon = (\text{Feature}_{\text{Predicted}} - (\alpha_{\text{FeatureFinal}} \times \text{Feature}_{\text{Final}} + y - \beta_{\text{FeatureFinal}}))^2 \]

• **Step 2: Calculate Z-scores, Nominal of Predicting Feature, Standard Deviation of Predicting Feature**

\[ Z_{\text{Lower}} = \frac{\text{Lower Tolerance}_{\text{FeatureFinal}} - \text{Nominal}_{\text{FeatureFinal}}}{\text{StandardDeviation}} \]

\[ Z_{\text{Upper}} = \frac{\text{Upper Tolerance}_{\text{FeatureFinal}} - \text{Nominal}_{\text{FeatureFinal}}}{\text{StandardDeviation}} \]

\[ \text{Nominal}_{\text{FeaturePredicted}} = \alpha_{\text{FeatureFinal}} \times \text{Nominal}_{\text{FeatureFinal}} + y - \beta_{\text{FeatureFinal}} + \varepsilon_{\text{Average}} \]

\[ \sigma_{\text{FeaturePredicted}} = \sqrt{((\alpha_{\text{FeatureFinal}})^2 \times (\sigma_{\text{FeatureFinal}}^2) + (\sigma_{\text{Error}}^2))} \]

• **Step 3: Calculate Tolerance Levels**

\[ \text{LowerTolerance}_{\text{FeaturePredicted}} = \text{Nominal}_{\text{FeaturePredicted}} + \sigma_{\text{FeaturePredicted}} \times Z_{\text{Lower}} \]

\[ \text{UpperTolerance}_{\text{FeaturePredicted}} = \text{Nominal}_{\text{FeaturePredicted}} + \sigma_{\text{FeaturePredicted}} \times Z_{\text{Upper}} \]