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

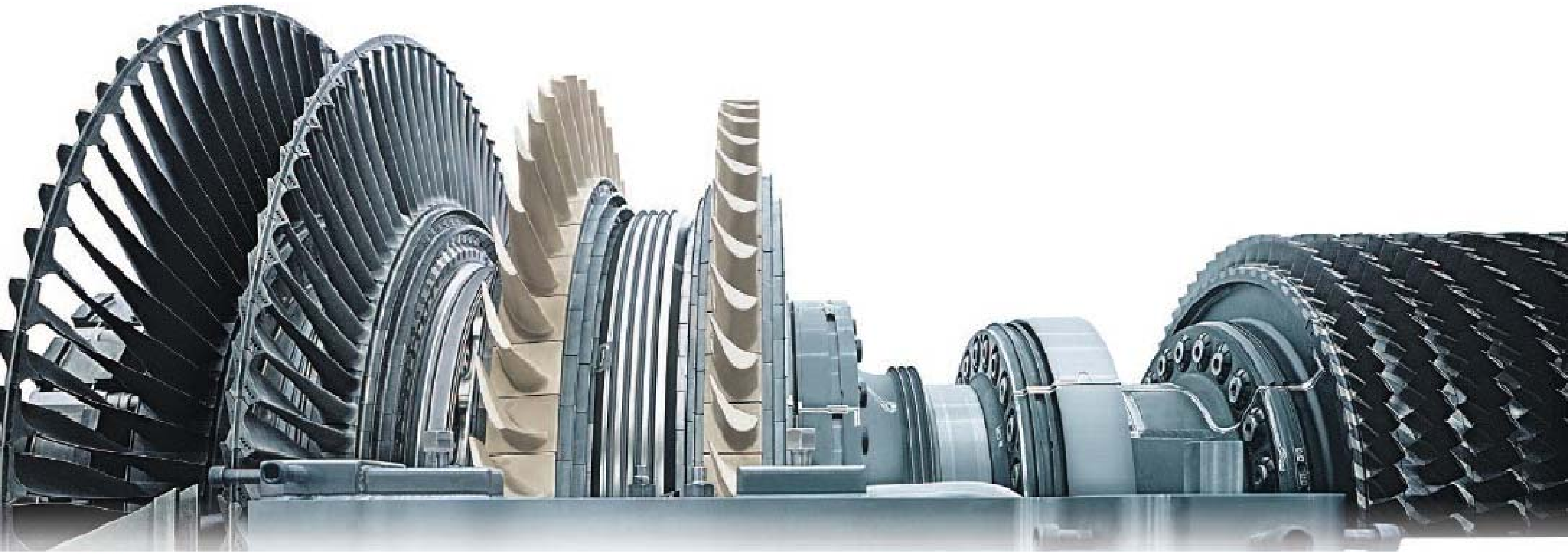
GE Contact 2: Bryan Graffagnini, Quality Manager

imagination at work

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

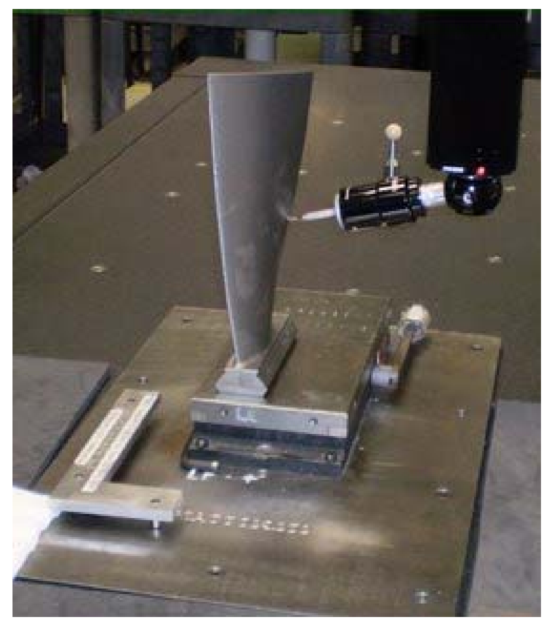
Forge Release → Rootmill & Lug Milling → Airfoil Milling → Polish → Testing → Shot Peen → Drag Finish → Tip Cut → Inspection

CMM (at Airfoil Milling)

CMM (at Inspection)

Forges

Coordinate Measuring Machine (CMM)



imagination at work

Problems

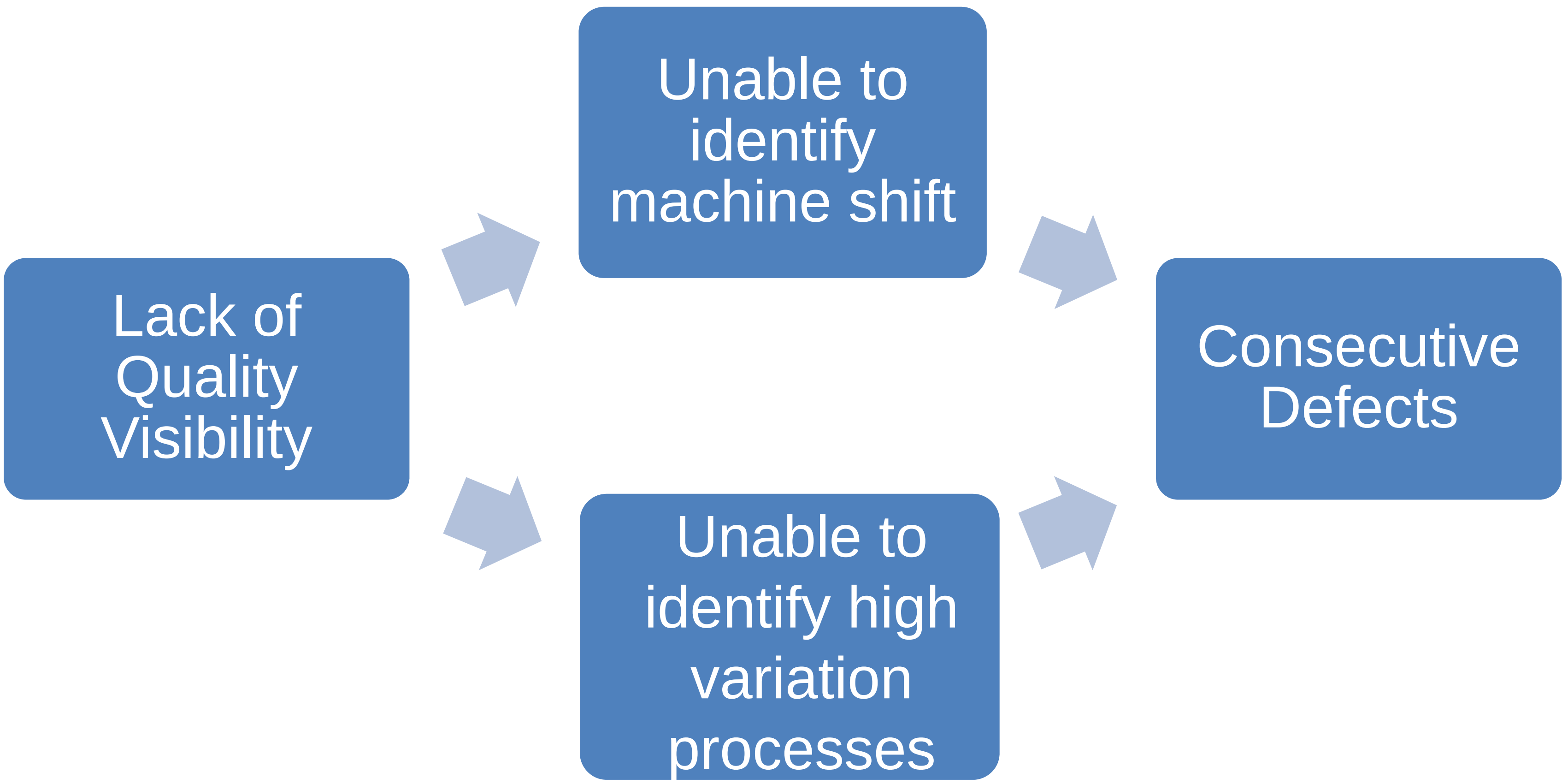
Lack of manager visibility	• Dashboard system • Detect trends and variation early
Excessive inspection time	• Correlation study • Eliminate redundant checkpoints
Inaccurate In-process tolerance levels	• Linear regression • Prevent loss of resources

Potential Savings: $830,000

imagination at work

Problem 1: Lack of quality visibility in the process

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



In 2008, this lack of visibility resulted in $200,000 in defect costs.

imagination at work

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

Part# 139E4981

Program After Machining

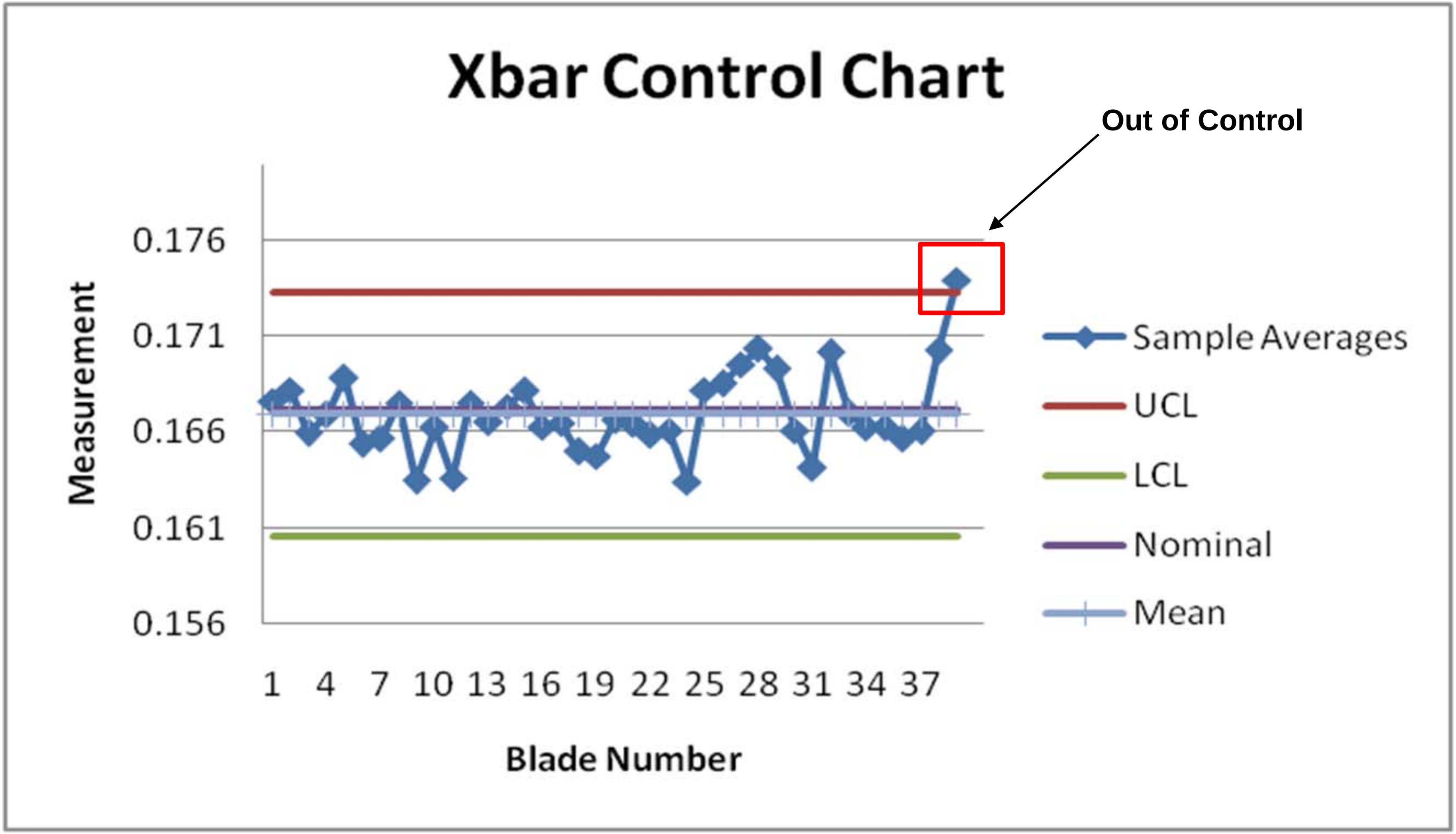
From Date: M/Day/Year 1/1/2008

To Date: M/Day/Year 1/1/2010

Characteristic LE Thickness

Section	Mean	Out	CMMed	Z-LT
VB	0.00392	0	27	6.43
VC	0.00381	0	27	6.34
VD	0.00399	0	27	7.05
VE	0.00447	0	27	6.25
VF	0.00496	0	27	5.58
VG	0.00520	0	27	4.74

Problem 1: Control Charts - X-bar and Range

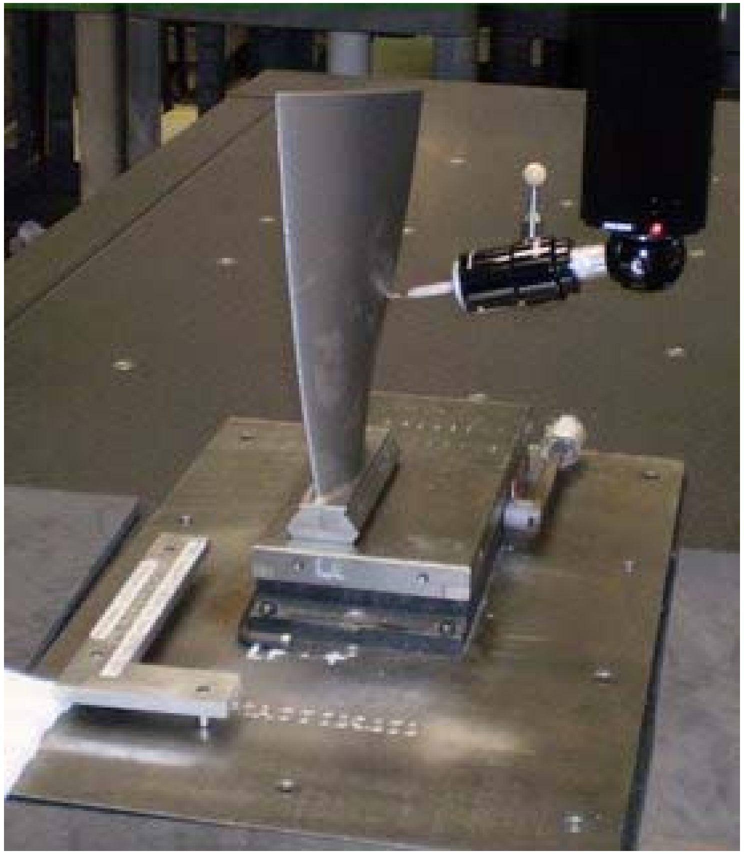


Problem 2: Excessive Inspection Time

~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



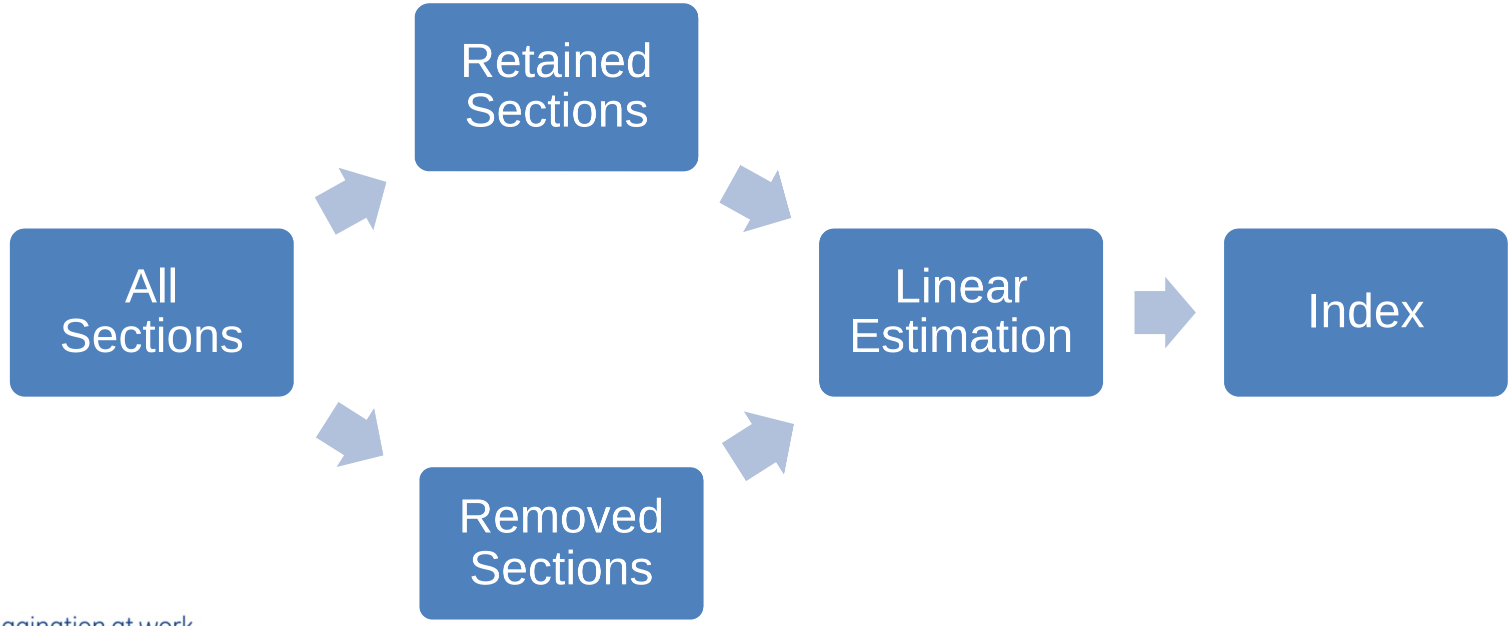
imagination at work

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

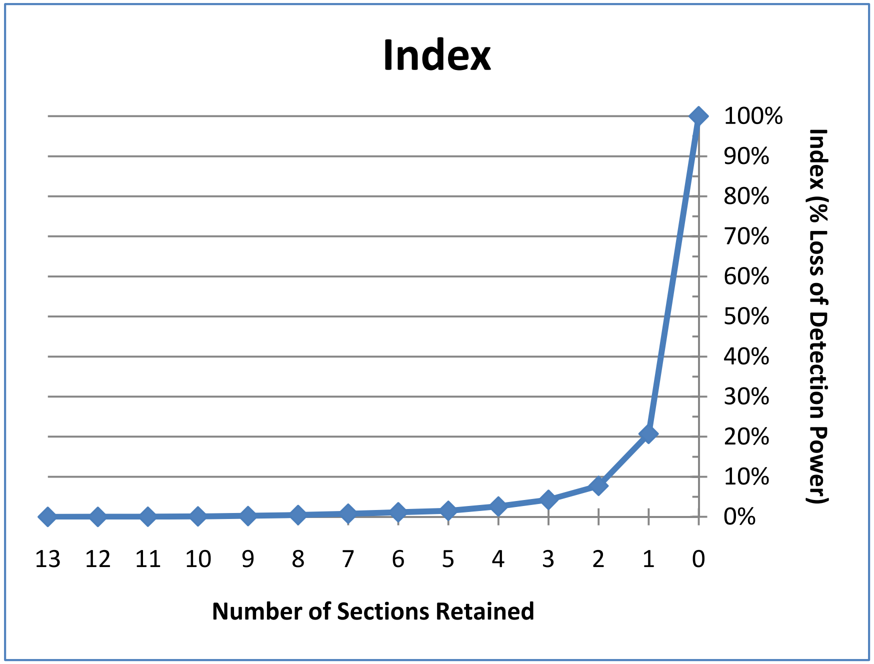
- Linear model estimates measurements of removed sections from those of retained sections
- Loss of detection power (Index) is calculated from the linear model as a function of retained sections
- Find optimal set of retained sections to minimize Index



imagination at work

Problem 2: Methodology

# Retained	Retained Sections	Index
13	CDEFGHJKLMNPR	0.00%
12	CDEFHJKLMNPR	0.03%
11	CEFGHJLMNPR	0.06%
10	CDEHJLMNPR	0.11%
9	CEGJLMNPR	0.18%
8	CDEJKNPR	0.30%
7	CDJKNPR	0.45%
6	CDJKNR	0.63%
5	CDKNR	0.82%
4	CHNR	1.46%
3	CFN	2.62%
2	CL	6.90%
1	L	16.78%
0		100.00%



imagination at work

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

Forge Release → Rootmill & Lug Milling → Airfoil Milling → Polish → Testing → Shot Peen → Drag Finish → Tip Cut → Inspection

AM CMM ← Inaccurate In-Process Tolerance Levels

Final CMM

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

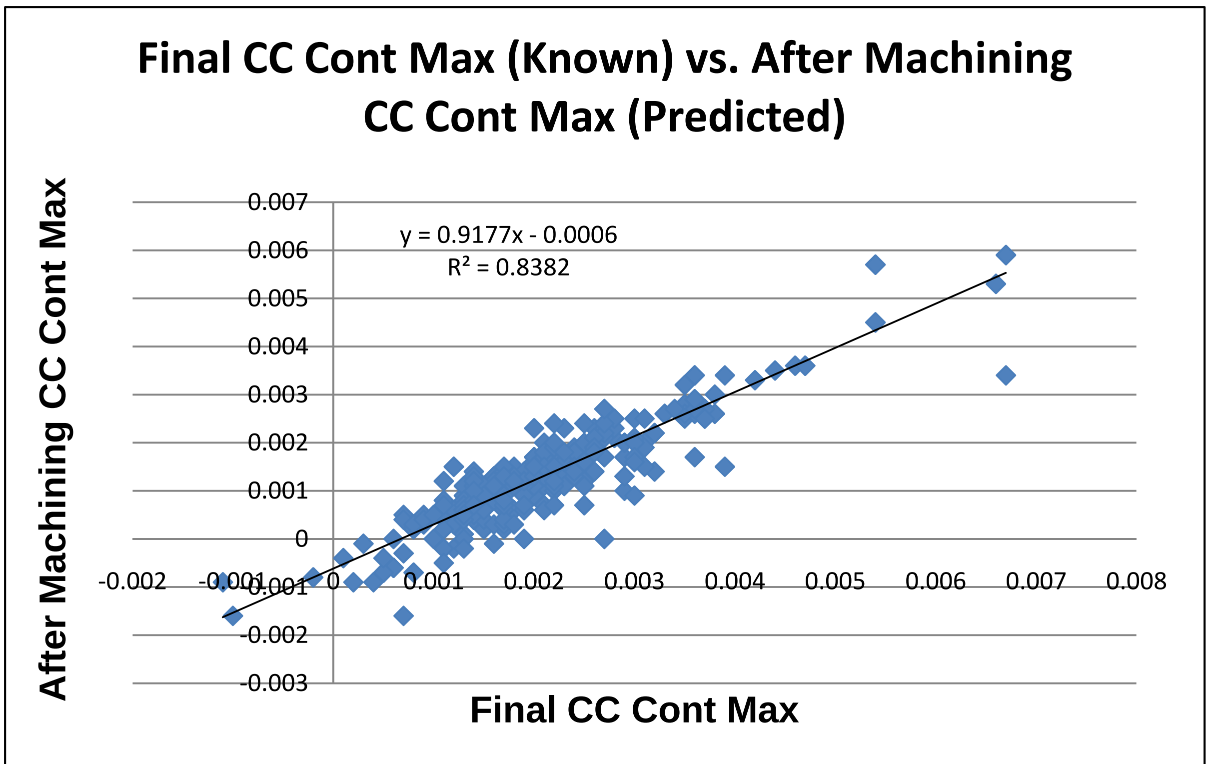
Problem 3: Correlation Study

- 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

Final Features	After Machining CC Cont Max
Final CC Cont Max	90%
Final CC Cont Min	70%
Final Centroid CC-CX	-14%
Final Centroid LE-TE	-9%
Final Chord	30%
Final CX Cont Max	74%
Final CX Cont Min	65%
Final LE Cont Max	59%
Final LE Cont Min	17%
Final LE Drop	-21%
Final LE Thickness	73%
Final Max Thickness	89%
Final TE Cont Max	59%
Final TE Cont Min	54%
Final TE Thickness	85%
Final Warp	-3%

Problem 3: Methodology

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



imagination at work

Problem 3: Results

Tolerance level for feature After Machining CC Cont Max

	Lower Tolerance	Upper Tolerance	Correlation
Final CC Cont Max	-0.0086	0.0105	90%
Final CC Cont Min	-0.0033	0.0084	70%
Final CX Cont Max	-0.0052	0.0075	74%
Final LE Thickness	-0.0005	0.0038	73%
Final Max Thickness	-0.0077	0.0114	89%
Final TE Thickness	-0.0042	0.0067	85%
Expected Tolerance	**-0.0071**	**0.0097**	
Conservative Tolerance	**-0.0039**	**0.0073**	

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

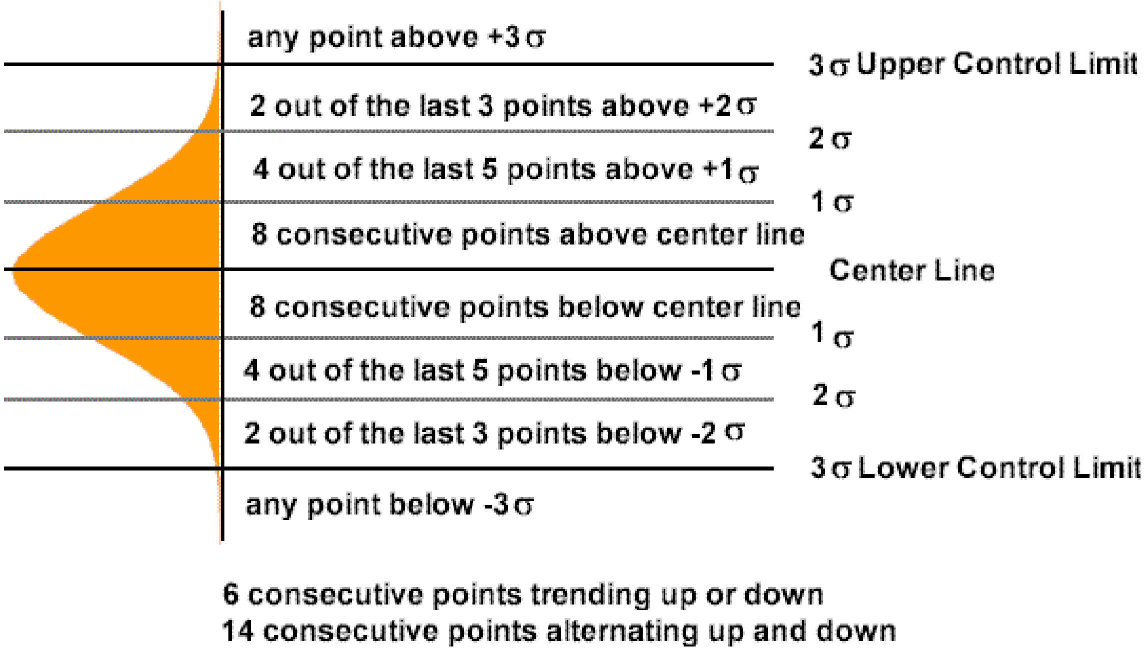
More accurate tolerance levels

- **$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

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

$$z = \min\left(\frac{.1772 - .166814}{.001881}, \frac{.166814 - .1572}{.001881}\right) = \min(5.52, 5.11) = 5.11$$

Appendix C – Problem 2: Correlation Formulas

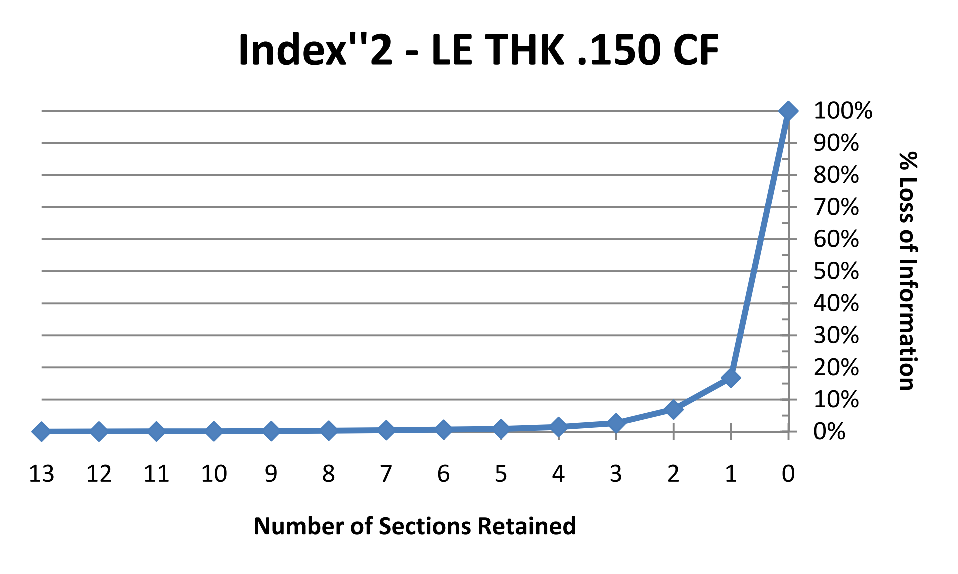
- K_{tot} – Covariance matrix of all measurements.
- K_{ret} – Covariance matrix of retained measurements (submatrix of K_{tot}).
- $K_{ret/tot}$ – Cross-covariance matrix between retained and all measurements (submatrix of K_{tot}).
- K_{spec} – Diagonal matrix based on the upper and lower specification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

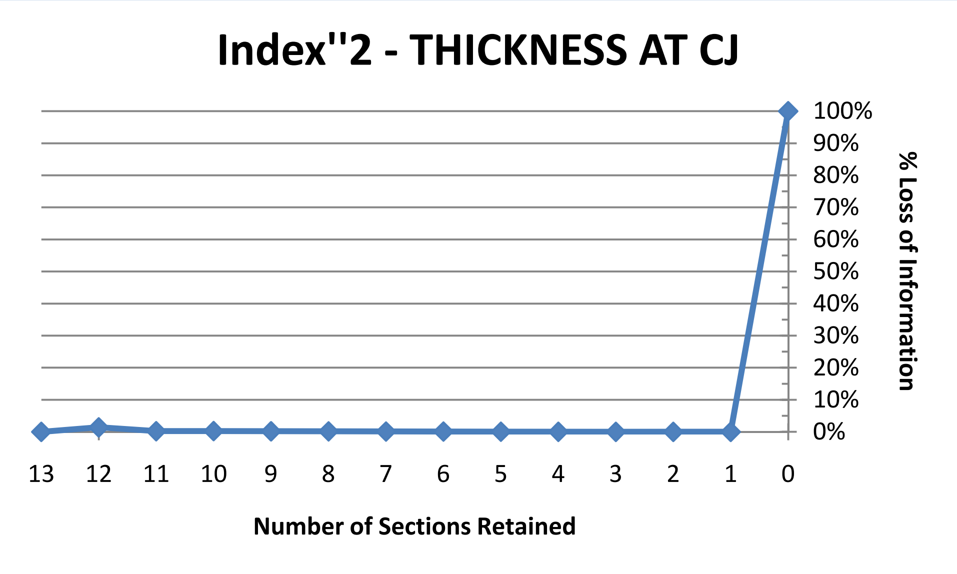
$$M_2'' = K_{spec}{}^{-1/2}[K_{tot} - K_{ret/tot}^T K_{ret}^{-1} K_{ret/tot}]K_{spec}^{-1/2}$$

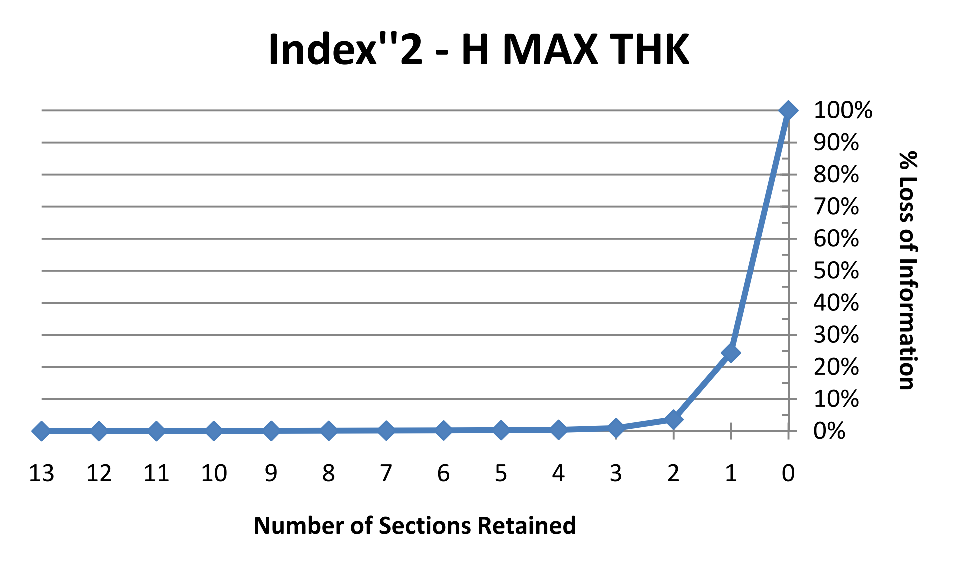
$$Index_2'' = \frac{trace(M_2'')}{K_{spec}^{-1/2} K_{tot} K_{spec}^{-1/2}}$$

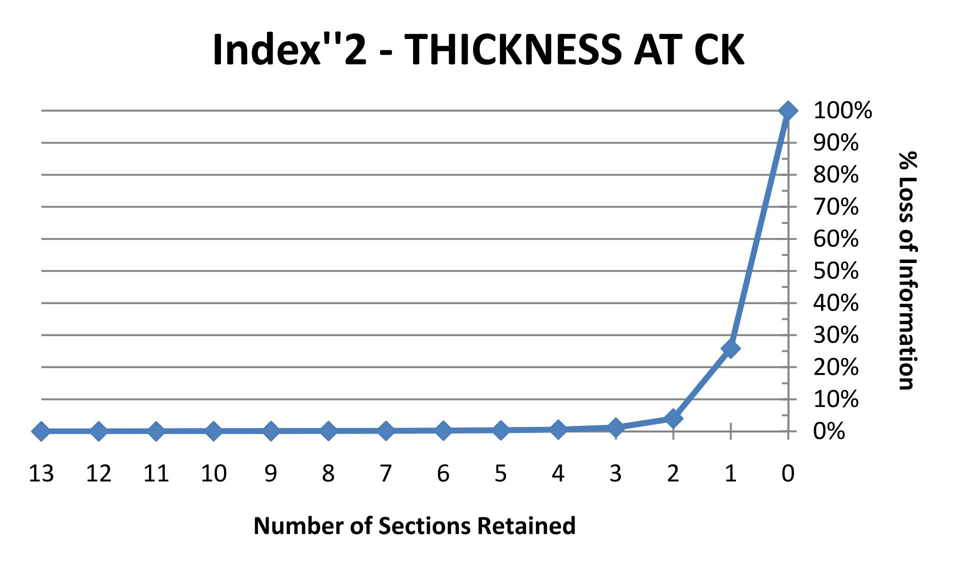
imagination at work

Appendix D – Problem 2: Correlation Graphs

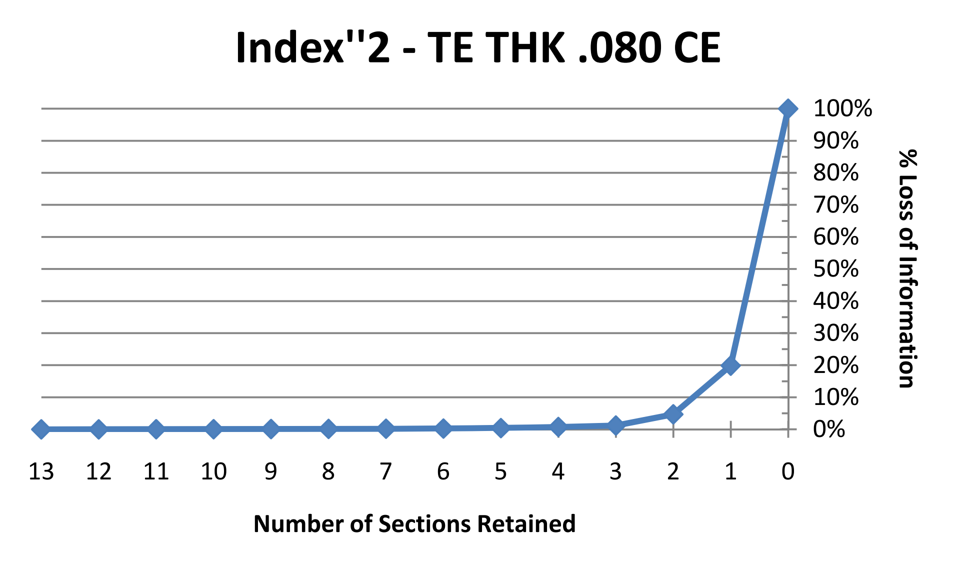


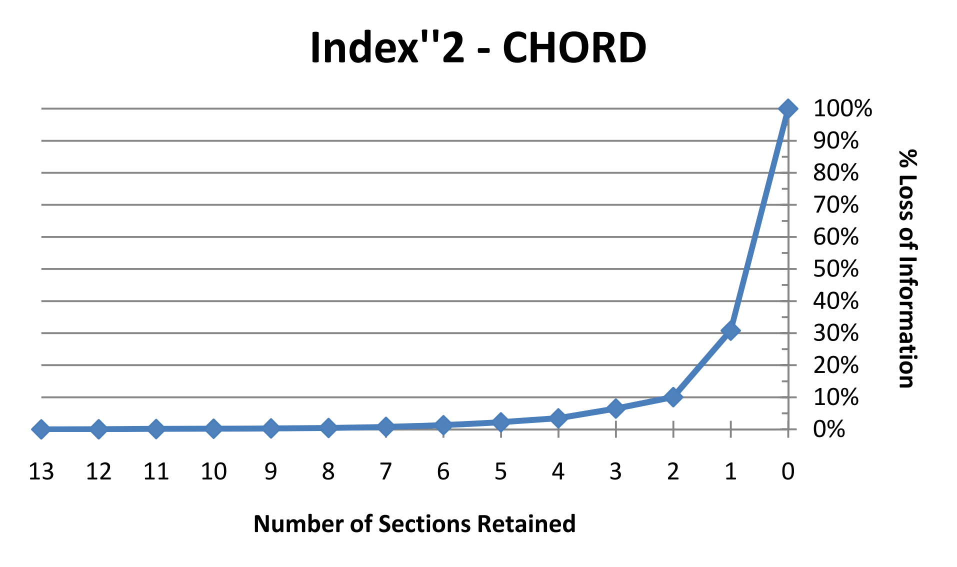


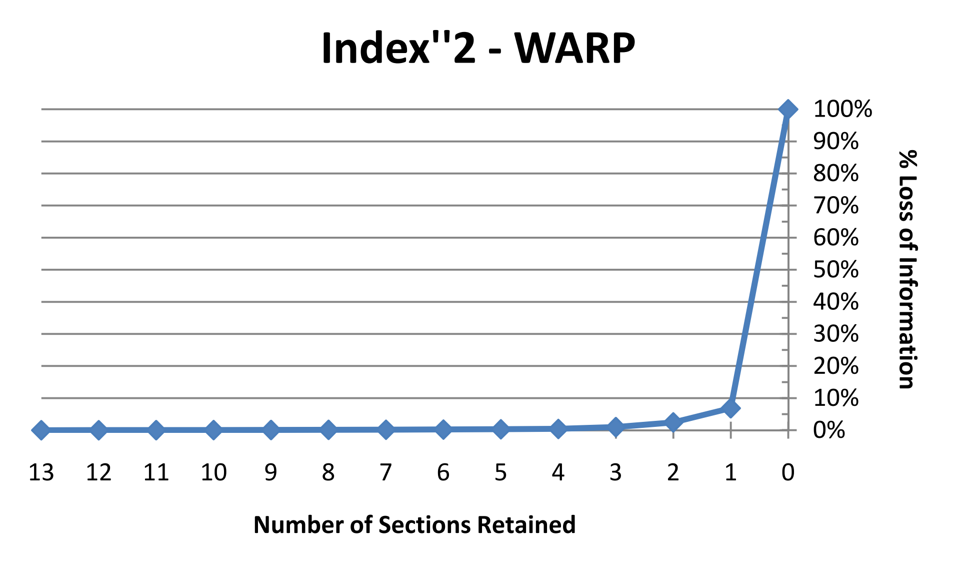


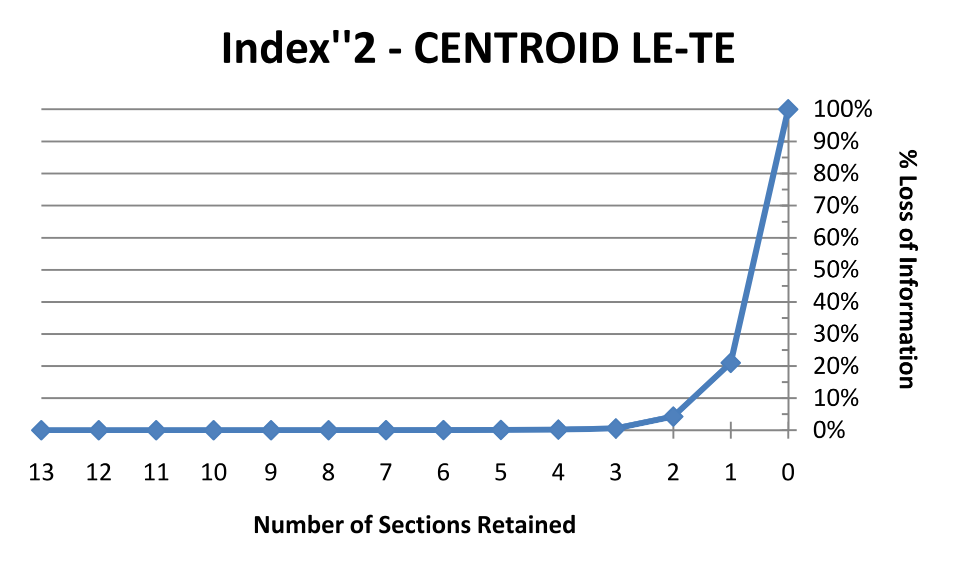


Appendix D – Problem 2: Correlation Graphs

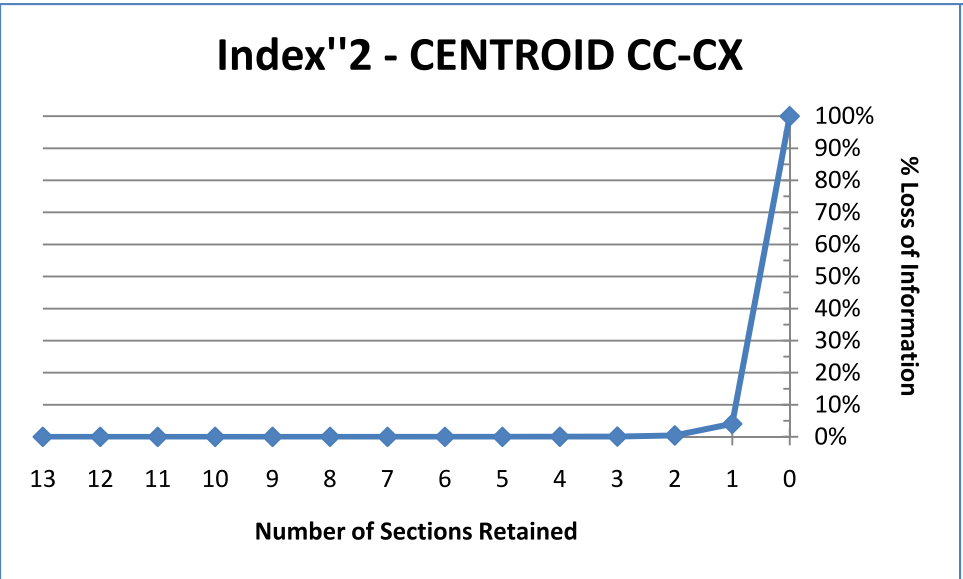


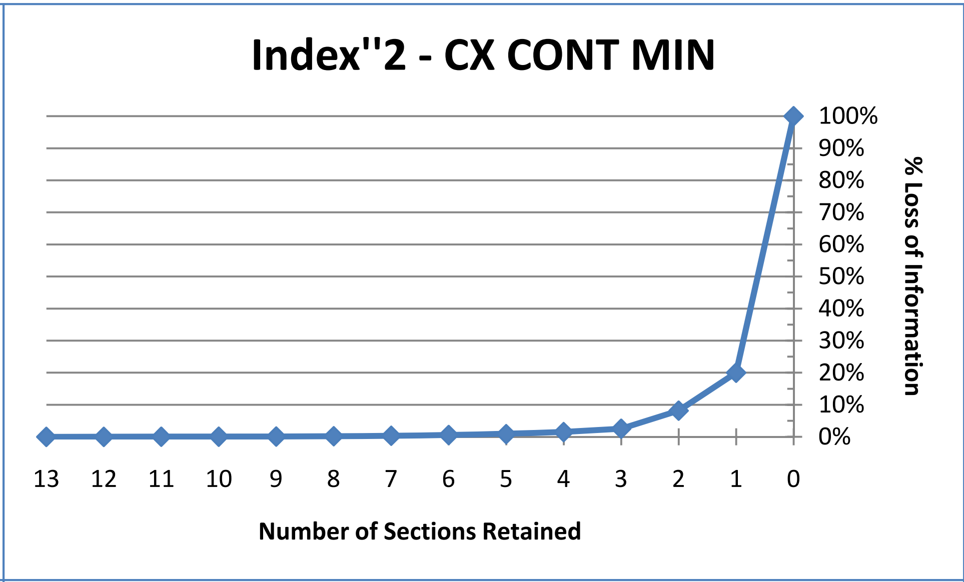


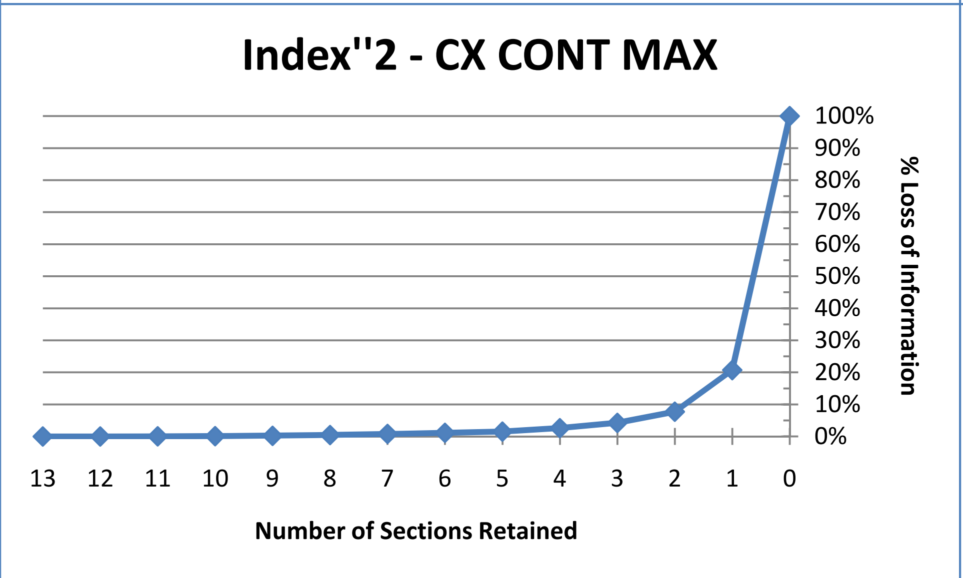


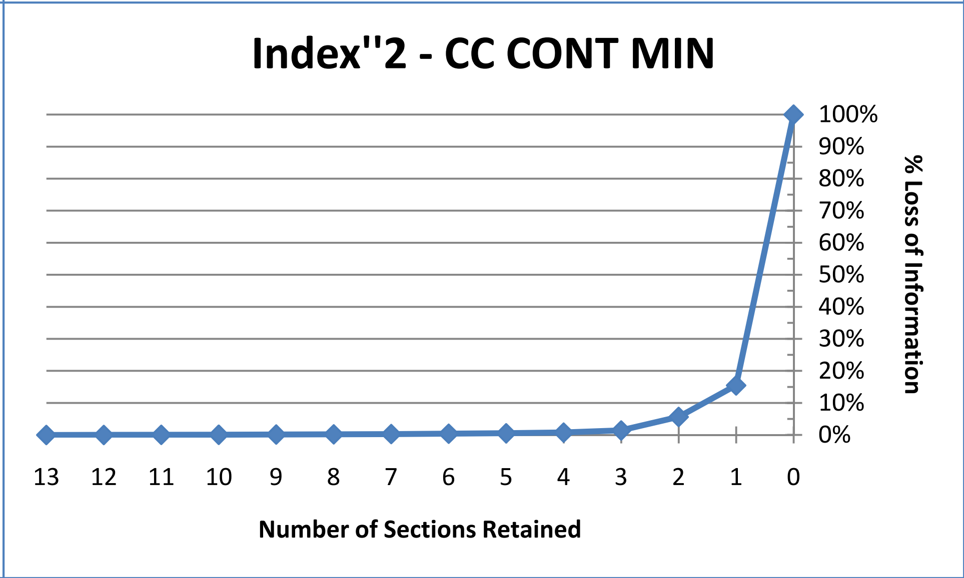


Appendix D – Problem 2: Correlation Graphs

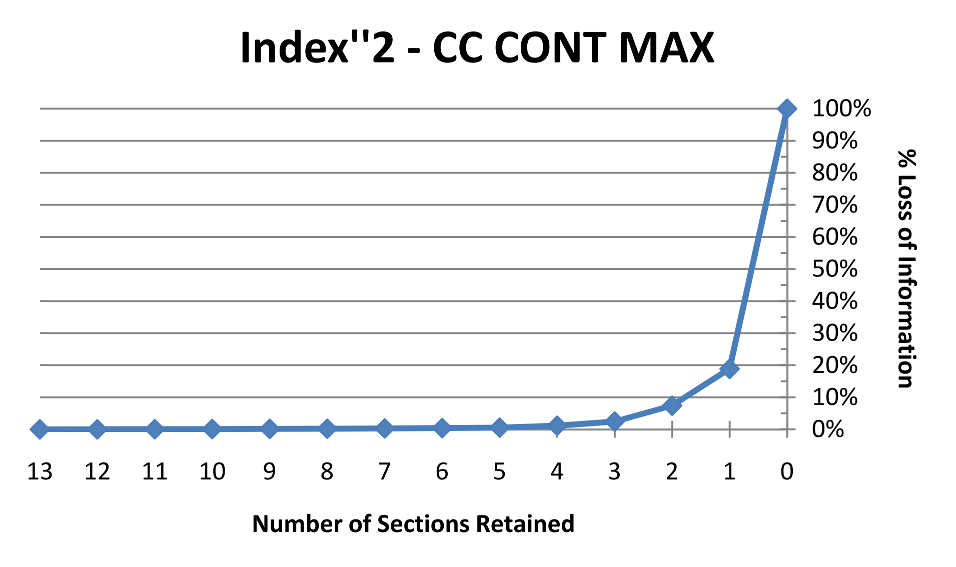


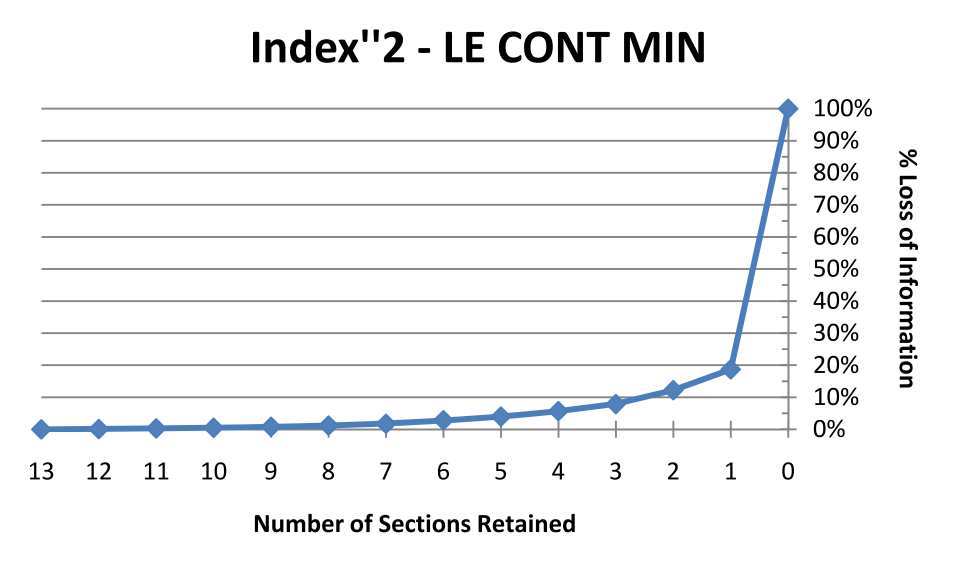


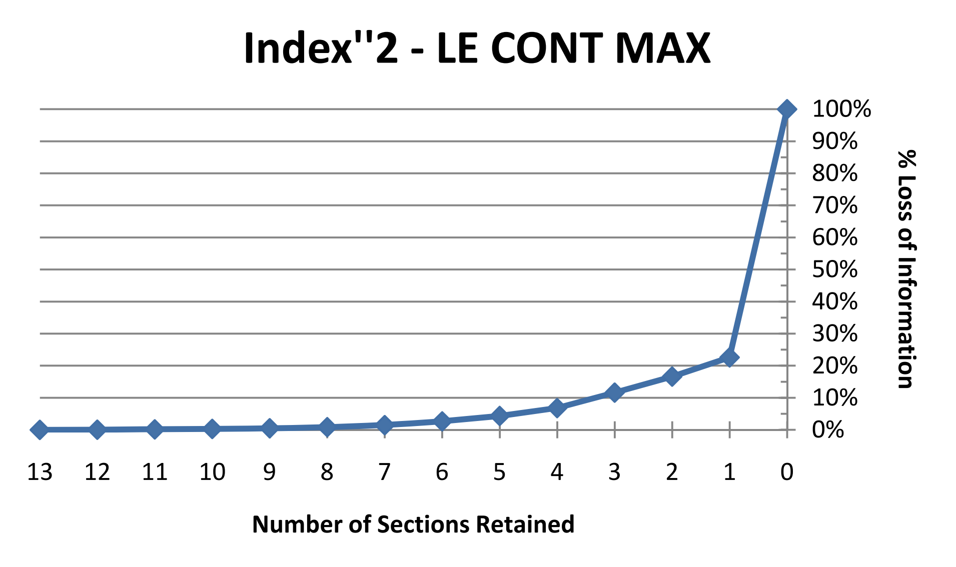


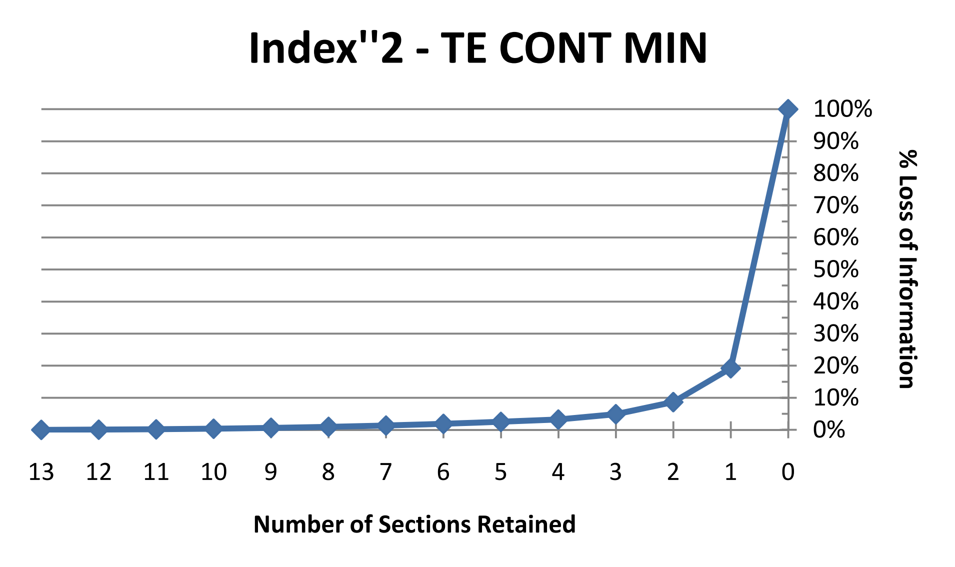


Appendix D – Problem 2: Correlation Graphs

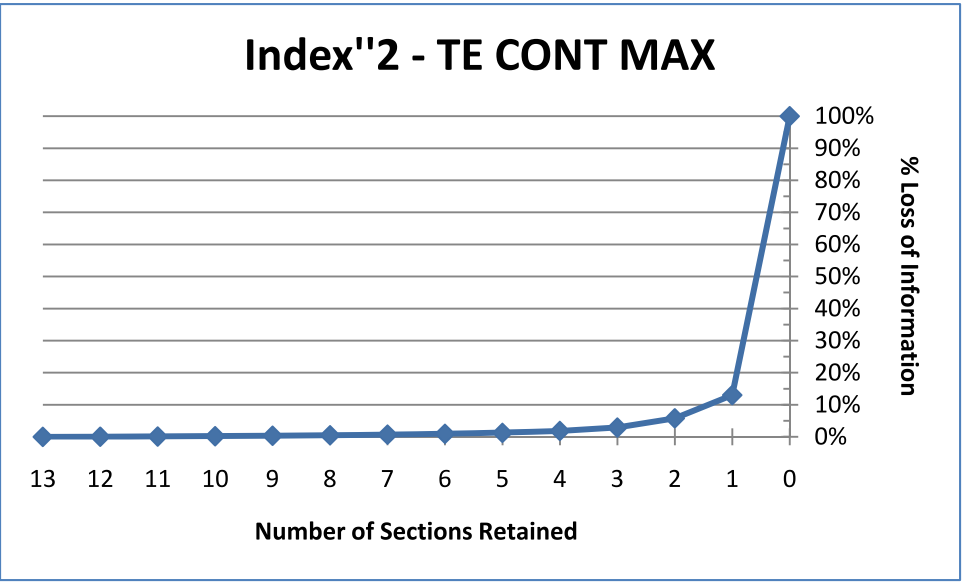








Appendix D – Problem 2: Correlation Graphs



Appendix E: Problem 3

- Step 1: Linear Regression

$$y = \alpha x + \beta + \varepsilon$$

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

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

$$Z_{Lower} = \frac{\text{Lower Tolerance}_{\text{FeatureFinal}} - \text{Nominal}_{\text{FeatureFinal}}}{\text{StandardDeviation}} \qquad Z_{Upper} = \frac{\text{Upper Tolerance}_{\text{FeatureFinal}} - \text{Nominal}_{\text{FeatureFinal}}}{\text{StandardDeviation}}$$

$$\text{Nominal}_{\text{FeaturePredicted}} = \alpha_{\text{FeatureFinal}} * \text{Nominal}_{\text{FeatureFinal}} + y - \beta_{\text{FeatureFinal}} + \varepsilon_{Average}$$

$$\sigma_{\text{FeaturePredicted}} = \sqrt{((\alpha^2{}_{\text{FeatureFinal}}) * (\sigma^2{}_{\text{FeatureFinal}}) + (\sigma^2{}_{\text{Error}}))}$$

- Step 3: Calculate Tolerance Levels

$$\text{LowerTolerance}_{\text{FeaturePredicted}} = \text{Nominal}_{\text{FeaturePredicted}} + \sigma_{\text{FeaturePredicted}} * Z_{\text{lower}}$$

$$\text{UpperTolerance}_{\text{FeaturePredicted}} = \text{Nominal}_{\text{FeaturePredicted}} + \sigma_{\text{FeaturePredicted}} * Z_{Upper}$$