Models for Evaluating and Monitoring Efficiency of Supply Chain Networks

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Axia Institute at Michigan State University

- Established in Fall 2015 with support from Dow Chemical, Dow Corning, and multiple Midland based companies

- Emphasis is on collaborative solutions-focused research for a variety of industry problems

- Took over as the faculty director in Fall 2018

- Leverage the strengths of Supply Chain Management Department (ranked # 1 in the United States)

Motivation

- Dow Chemical's focus on efficiency of supply chain networks:
  - Current methods mainly focusing on cost optimization
  - Evaluate supply chain network performance in a more holistic manner
  - Develop an approach for monitoring and improving network performance
  - Redesign trigger

Performance Management

- Performance management literature (operations, engineering, and cost accounting) emphasizes the use of multiple measures (Kaplan and Norton 1996; Nanni et al. 1992; Adams et al. 1995)

- Kueng (2000) points that:
  - Performance is multidimensional and cannot be assessed by a single indicator and
  - Performance indicators are not independent (cost, quality, and time tradeoffs)

- SCOR model focuses on multiple supply chain metrics at strategic, tactical, and operational levels (Supply Chain Council 2004)

Supply Chain Performance, Structure and Firm Performance

- Impact of supply chain responsiveness and uncertainty on firm performance (Wagner et al. 2012)
- Supply chain flexibility (sourcing, manufacturing, logistics) and firm performance (Sanchez and Perez 2005; Merschmenn and Thonemann 2011)
- Supply chain configurations (decentralized vs. centralized designs and direct vs. indirect shipments) and impact on performance (Chiu and Kremer 2014; Rosales et al. 2013)
- Supply chain network design with cost and reliability tradeoffs (Yildiz et al. 2014); cost and time tradeoffs (Arntzen et al. 1995)

Contribution

- Given the emphasis on network design and its impact on multivariate performance:
  - We focus on developing an approach for effectively evaluating and monitoring the realized efficiency of supply chain networks based on multiple factors (aggregated metric)
  - Effectively consider interrelationships among factors (tradeoffs)
  - Assist in identifying any systematic trends/patterns in efficiency
  - Help trigger a network redesign need to improve performance

Case Company Details & Data Gathering Efforts

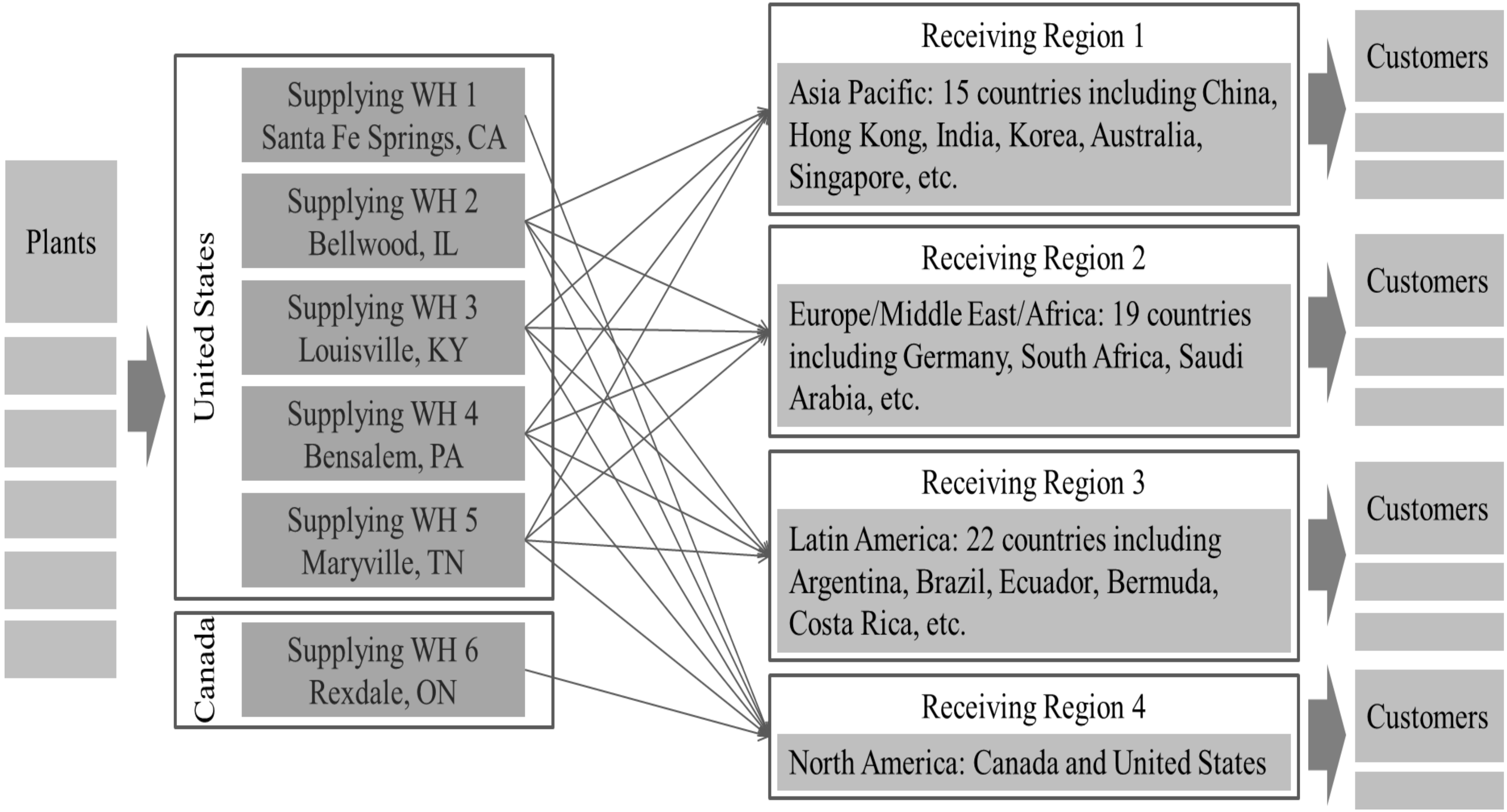
- Multinational Chemical Corporation
- Identified a Business Unit with the assistance of Case Company Research Team
- Multiple on-site and conference call meetings with the Research Team and the Business Unit Management Team to finalize the factors to utilize in the study and related data requirements
- Significant amount of effort in data gathering- multiple databases/systems

Supply Chain Network Details

- Network:
  - 6 manufacturing plants
  - 6 warehouses
  - 869 customers
  - 699 products

- Dow’s network optimization model:
  - Objective: Minimize transportation cost
  - Decisions: Reassign customers to existing warehouses

Supply Chain Network Details



Factors for Network Efficiency Analysis

- Inputs:
  - Total Inventory ($)
  - Transportation Cost ($/lb.)
- Outputs:
  - Customer Service Level (on-time delivery rate, %)
  - Throughput (sum of delivered net weight, lb.)

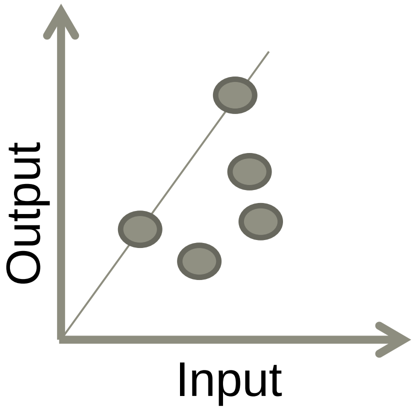
Data

- Approximately 3 years of data
- Before Supply Chain Network (SCN) Optimization
  - 16 months
- After SCN Optimization
  - 17 months

Methodology

- Multi-factor productivity models - Data Envelopment Analysis
- Statistical Process Control methods
- Non-parametric statistical tests and clustering methods
- Extensions based on cross-efficiency models

Efficiency Evaluation – CCR DEA Model



$$\max \quad \frac{\sum_{k=1}^{s} v_k y_{kp}}{\sum_{j=1}^{m} u_j x_{jp}}$$

$$s.t \quad \frac{\sum_{k=1}^{s} v_k y_{ki}}{\sum_{j=1}^{m} u_j x_{ji}} \leq 1, \quad \forall i$$

$$v_k, u_j \geq 0 \quad \forall k,\ j$$

$$\longrightarrow$$

$$\max \quad \sum_{k=1}^{s} v_k y_{kp}$$

$$s.t \quad \sum_{j=1}^{m} u_j x_{jp} = 1$$

$$\sum_{k=1}^{s} v_k y_{ki} - \sum_{j=1}^{m} u_j x_{ji} \leq 0, \quad \forall i$$

$$v_k, u_j \geq 0 \quad \forall k,\ j$$

where: p is the unit being evaluated; s represents the number of outputs; m represents the number of inputs; y_{ki} is the amount of output k provided by unit i; x_{ji} is the amount of input j used by unit i; v_k and u_j are the weights given to output k and input j, respectively.

CCR DEA Model (Dual Form)

$$\min \quad \theta$$

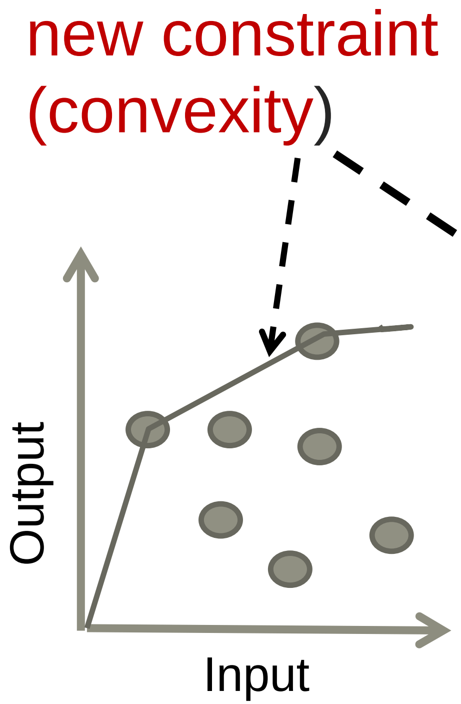
$$s.t \quad \sum_i \lambda_i x_{ji} \leq \theta x_{jp} \quad \forall j$$

$$\sum_i \lambda_i y_{ki} \geq y_{kp} \quad \forall k$$

$$\lambda_i \geq 0 \quad \forall i$$

where: θ represents the efficiency score of unit p; λs represent the dual variables that identify the benchmarks for inefficient units.

Efficiency Evaluation - BCC DEA Model



$$\min \quad \theta$$

$$s.t \quad \sum_i \lambda_i x_{ji} \leq \theta x_{jp} \quad \forall j$$

$$\sum_i \lambda_i y_{ki} \geq y_{kp} \quad \forall k$$

$$\sum_i \lambda_i = 1$$

$$\lambda_i \geq 0 \quad \forall i$$

where: θ represents the efficiency score of unit p; λs represent the dual variables that identify the benchmarks for inefficient units.

Windows Analysis

- Temporal data in efficiency evaluation
- Network is treated as a different entity in each time period
- Network is compared to itself over time

Individual Control Chart (X-Chart)

- Sample size of 1 (single efficiency score in each period)

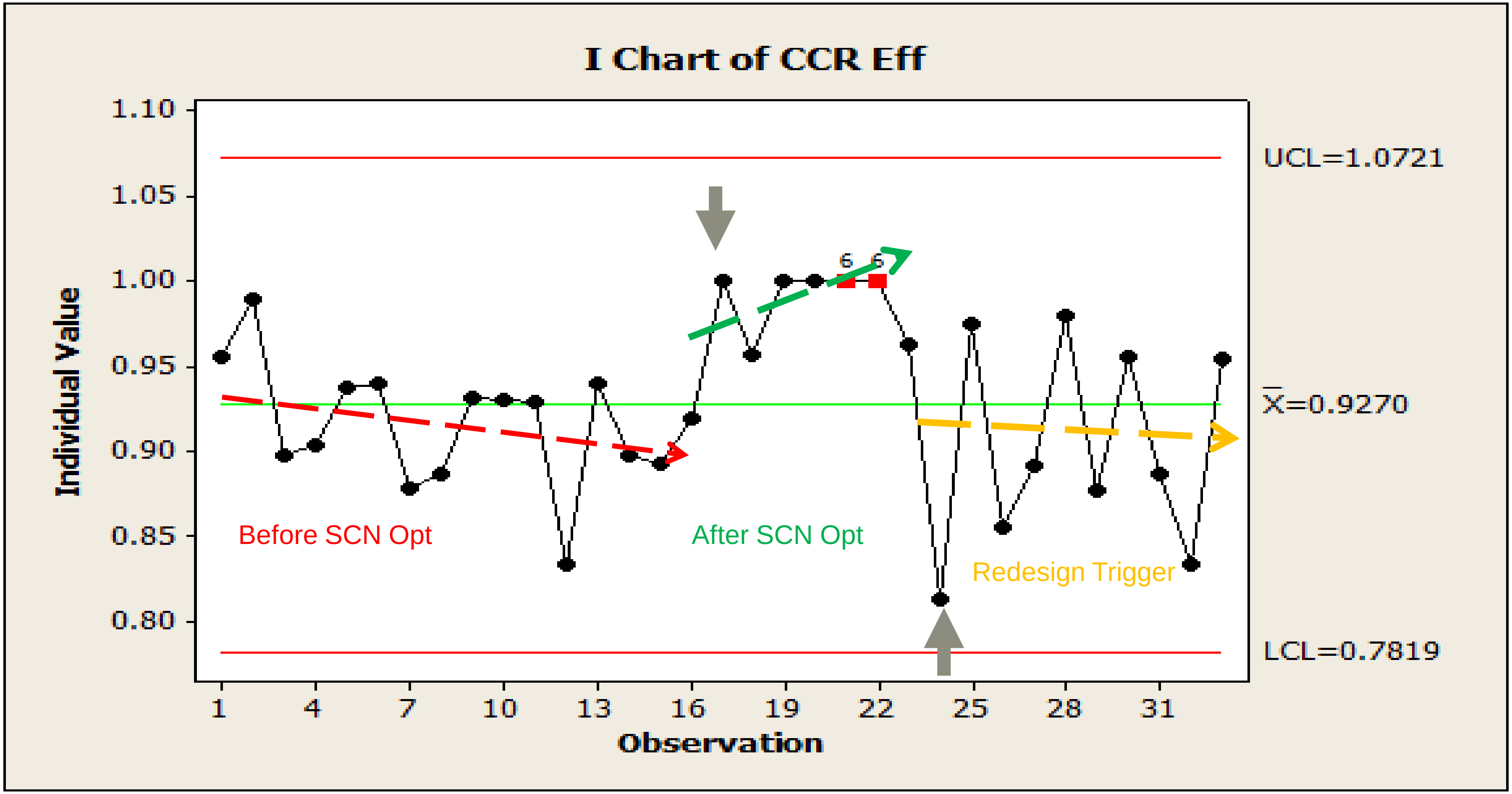
$$\mathrm{UCL} = \bar{x} + 3\underbrace{\frac{\overline{\mathrm{MR}}}{d_2}}_{\text{Standard deviation}}$$

$$\mathrm{CL} = \bar{x}$$

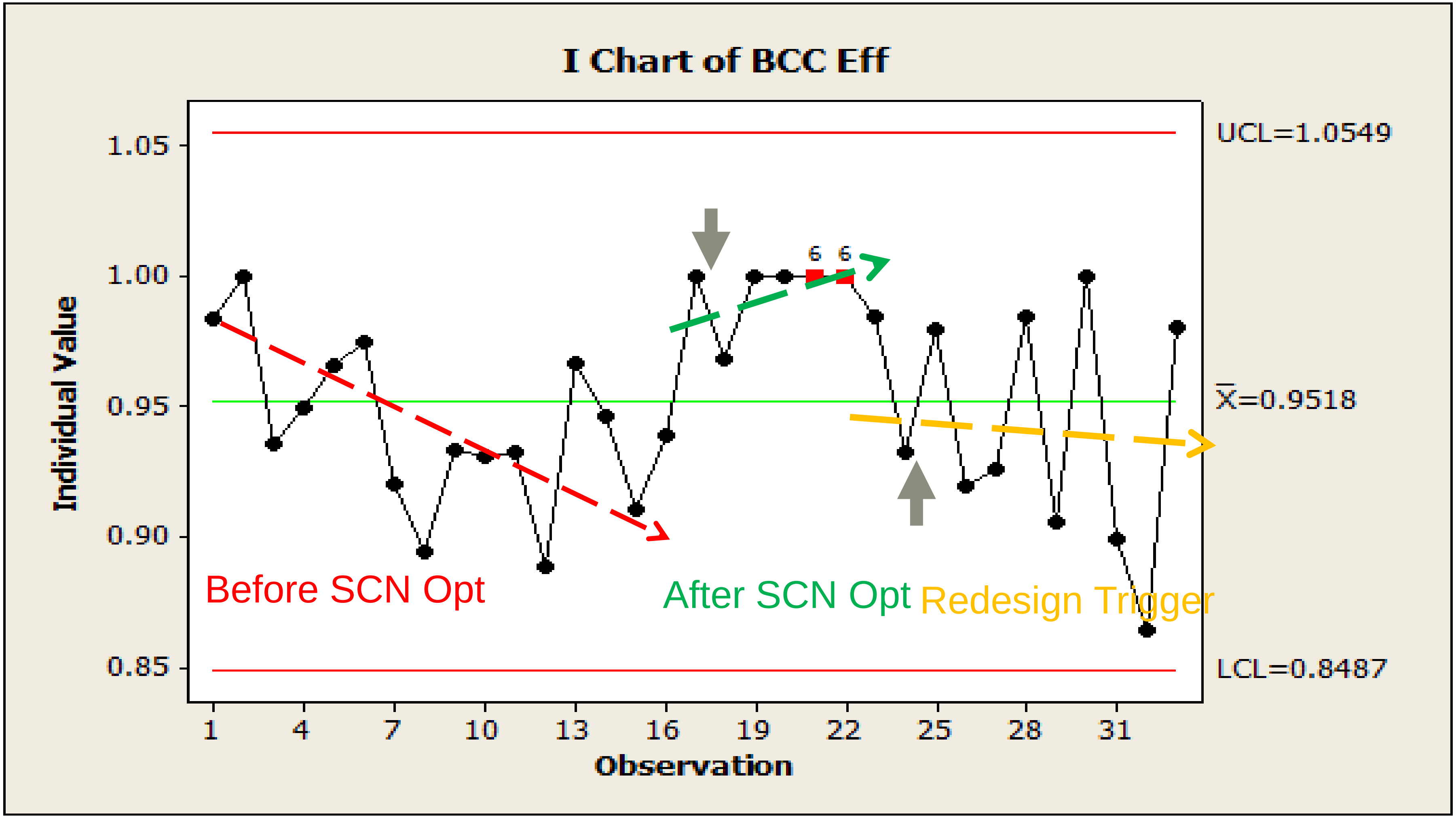
$$\mathrm{LCL} = \bar{x} - 3\frac{\overline{\mathrm{MR}}}{d_2}$$

Where: $$\overline{\mathrm{MR}} = \frac{\sum_{i=1}^{m} \mathrm{MR}_i}{m}$$

Supply Chain Network Efficiency Results – Constant Returns to Scale



Supply Chain Network Efficiency Results – Variable Returns to Scale



Before and After Efficiency Differences – Mann Whitney Test

- Efficiency scores (normality issues)
- Nonparametric test for differences in distributions - Mann Whitney
- Hypotheses:
  - H_0: *No difference in efficiency scores between the two segments of data*
  - H_1: *Efficiency scores of one segment is higher than the other segment*

Before and After Efficiency Differences – Mann Whitney Test 1

- After optimization CCR efficiency scores are statistically better than before optimization scores
  - $n_1 = 16, n_2 = 7, p{-}value = 0.0004^{***}$

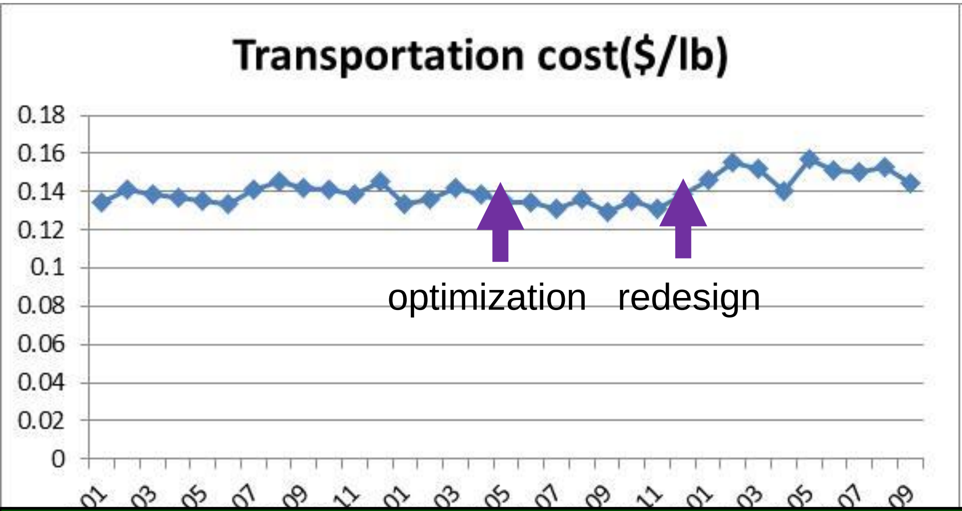
- After optimization BCC efficiency scores are statistically better than before optimization scores
  - $n_1 = 16, n_2 = 7\ p{-}value = 0.0011^{***}$

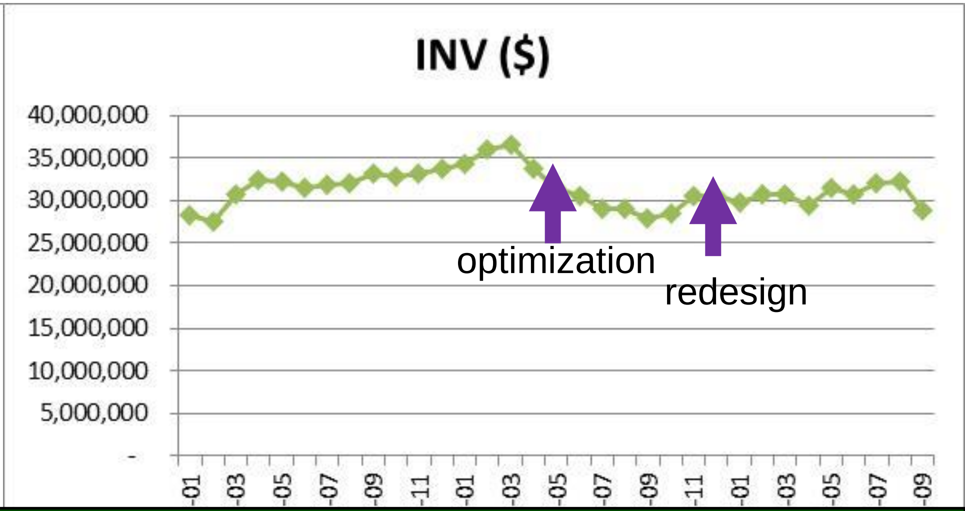
Before and After Efficiency Differences – Mann Whitney Test 2

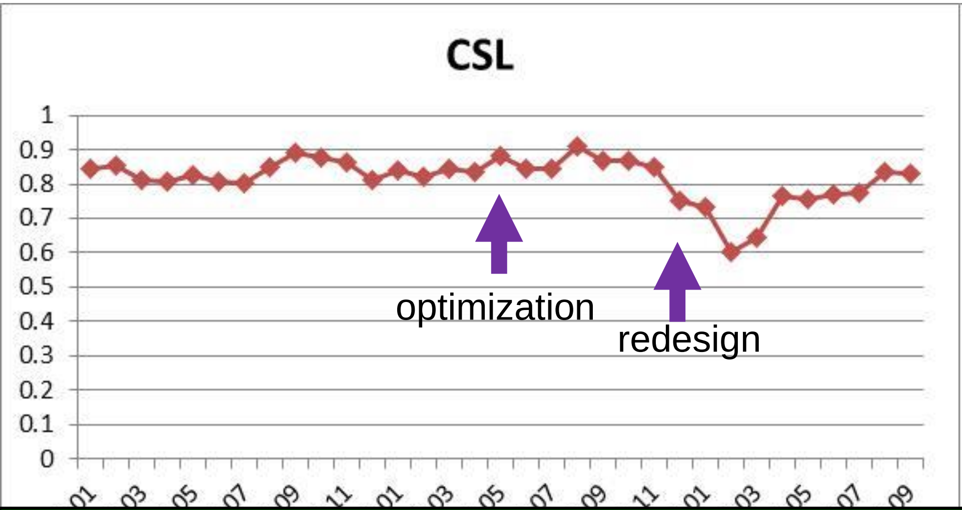
- After optimization CCR efficiency scores are statistically better than redesign trigger range scores
  - $n_1 = 7, n_2 = 10, p\text{−}value = 0.0029^{***}$

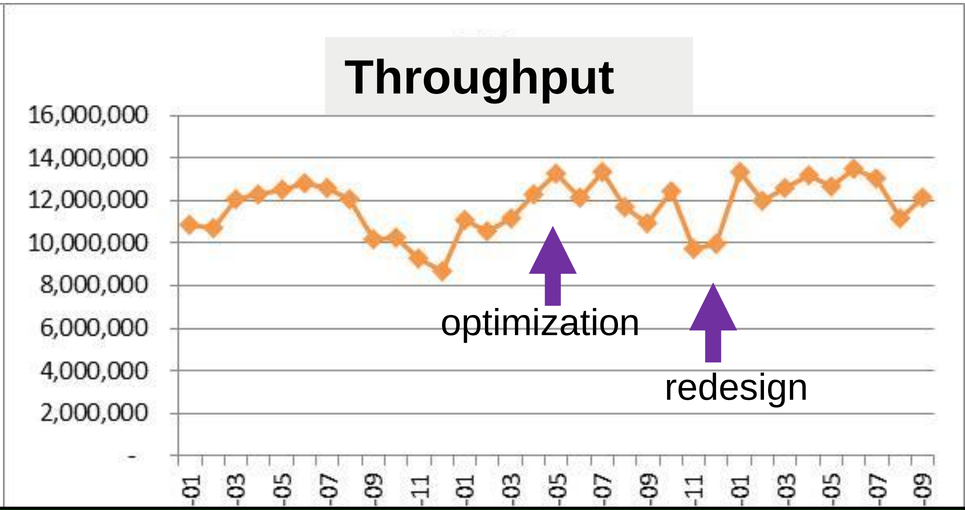
- After optimization BCC efficiency scores are statistically better than redesign trigger range scores
  - $n_1 = 7, n_2 = 10, p\text{−}value = 0.0112^{**}$

Individual Factors









Some Observations

- Each of the individual factors may be in control but the joint impact may show something different!

- After optimization: Transportation cost decreasing, inventory decreasing

- Redesign trigger: Transportation cost increasing, CSL decreasing, inventory increasing
  - Disruptions such as winter storm and the subsequent transportation capacity tightness might be a factors

Impact of Disruptions

- The events include a wide range of failures:
  - Quality, transportation, inventory, production, documentation, and packaging issues
  - For each incident, the amount of products that were impacted was recorded. We used this information as a proxy for the size of the impact of the failure

- Hypotheses:
  - H_0: *No difference in mean impacted product amounts between the two segments of data (Before SCN Opt vs. After SCN opt, Redesign Trigger vs. After SCM Opt)*
  - H_1: *First segment results in a higher mean impacted product amounts than the second segment*

Impact of Disruptions

- Failed to reject the Null Hypotheses in both cases (p-values of 0.17 and 0.13, respectively)

	Mean	Std. Deviation
Before SCN Opt.	211427.1	46425.0
After SCN Opt.	183025.1	67329.4
Redesign Trigger	225537.6	54460.9

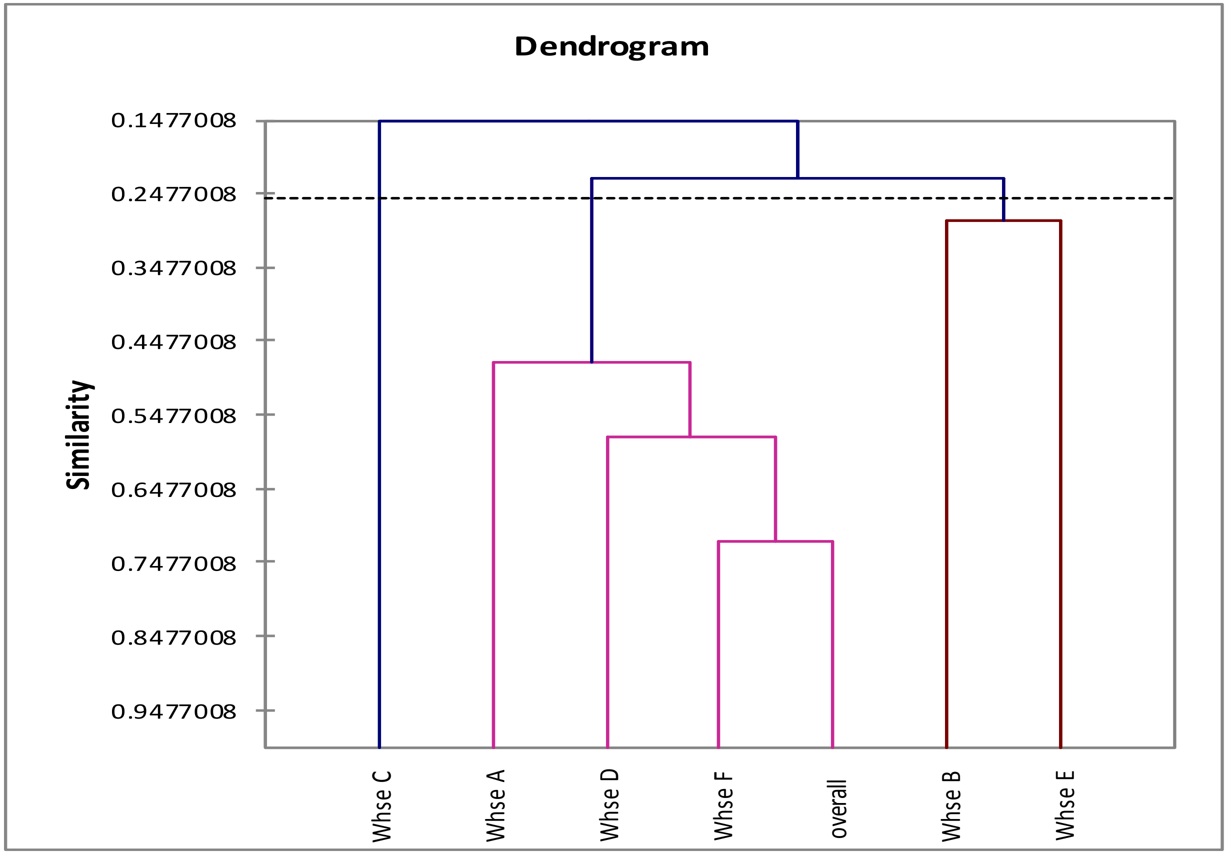
Warehouses vs. Network Efficiency

- Compared the overall network efficiency in each period to individual warehouse efficiencies
  - Efficiency evaluations for 6 x 33 units

- Clustering approach to investigate similarities in terms of network and warehouse efficiencies

- Helps focus on improvement strategies and resource allocations

Dendrogram based on CCR Scores



- Similarity: Spearman Correlation Coefficient; Agglomeration: Unweighted Pair-Group Average
- Cluster 1- A, D, F, Overall; Cluster 2- B, E; Cluster 3- C
- Initial focus is on improving the efficiencies of F, D, and A

Tukey's Multiple Comparisons: Warehouses

Transportation Cost (Low to High)

WH/Group	1	2	3	4
C	X			
E	X			
A	X	X		
F		X	X	
D			X	X
B				X

Inventory (Low to High)

WH/Group	1	2	3	4
B	X			
C	X			
E		X		
A			X	
D				X
F				X

Customer Service (High to Low)

WH/Group	1	2	3
C	X		
B	X	X	
F		X	
E		X	X
A		X	X
D			X

Throughput (High to Low)

WH/Group	1	2	3	4	5
F	X				
D		X			
A			X		
E				X	
B					X
C					X

- Warehouse F facing high inventory and transportation costs with lower customer service levels but high throughput rates (p-value < 0.01)

Limitations with CCR and BCC Models

- Unrestricted weight flexibility
- A unit can emphasize on few input and output factors in achieving high efficiency scores
- Cross-efficiencies can appease this issue

Cross-Efficiency Evaluations

- Cross efficiency in DEA allows for effective discrimination between niche performers and good overall performers

- Cross efficiency score of a unit represents how well the unit is performing with respect to the optimal weights of another unit

- A unit that achieves high cross efficiency scores is a good overall performer

Cross-Efficiency Matrix

DMU	1	2	3	N
1	Θ_{11}	Θ_{12}	Θ_{13}	Θ_{1N}
2	Θ_{21}	Θ_{22}	Θ_{23}	Θ_{2N}
3	Θ_{31}	Θ_{32}	Θ_{33}	Θ_{3N}
N	Θ_{N1}	Θ_{N2}	Θ_{N3}	Θ_{NN}

Efficiency score of DMU 2 when evaluated with the optimal weights of DMU 1

Cross-Efficiency Evaluations

- Weights obtained from the CCR model may not be unique, which undermines the usefulness of the cross-efficiency matrix

- We utilize game models to obtain a robust set of weights for cross efficiency evaluations

- Set of weights that not only maximizes the efficiency of a unit but in some sense minimizes the efficiency of all other units

Cross-Efficiency Models – Blanket Formulations

Aggressive

$$\min \sum_{k=1}^{s}\left(v_k \sum_{i\neq p} y_{ki}\right)$$

$$s.t \quad \sum_{j=1}^{m}\left(u_j \sum_{i\neq p} x_{ji}\right)=1$$

$$\sum_{k=1}^{s} v_k y_{ki} - \sum_{j=1}^{m} u_j x_{ji} \le 0, \quad \forall i \neq p$$

$$\sum_{k=1}^{s} v_k y_{kp} - \theta_p \sum_{j=1}^{m} u_j x_{jp} = 0$$

$$v_k, u_j \ge 0 \quad \forall k, j$$

Benevolent

$$\max \sum_{k=1}^{s}\left(v_k \sum_{i\neq p} y_{ki}\right)$$

$$s.t \quad \sum_{j=1}^{m}\left(u_j \sum_{i\neq p} x_{ji}\right)=1$$

$$\sum_{k=1}^{s} v_k y_{ki} - \sum_{j=1}^{m} u_j x_{ji} \le 0, \quad \forall i \neq p$$

$$\sum_{k=1}^{s} v_k y_{kp} - \theta_p \sum_{j=1}^{m} u_j x_{jp} = 0$$

$$v_k, u_j \ge 0 \quad \forall k, j$$

Where θ_p is the relative efficiency score of DMU p obtained from the CCR model

X-bar Chart

- UCL, LCL $= \bar{\bar{x}} \pm 3 \frac{\bar{R}}{d_2\sqrt{n}}$

- where $\bar{\bar{x}}$ is the average of all the cross-efficiency scores; d_2 is the table value obtained from standard quality control tables; $\bar{R}$ is the mean sample range, which is calculated as:

- $\bar{R} = \left(\frac{\sum_{i=1}^{m} R_i}{m}\right)$, where R_i is the difference between the largest and smallest cross efficiency scores

R Chart

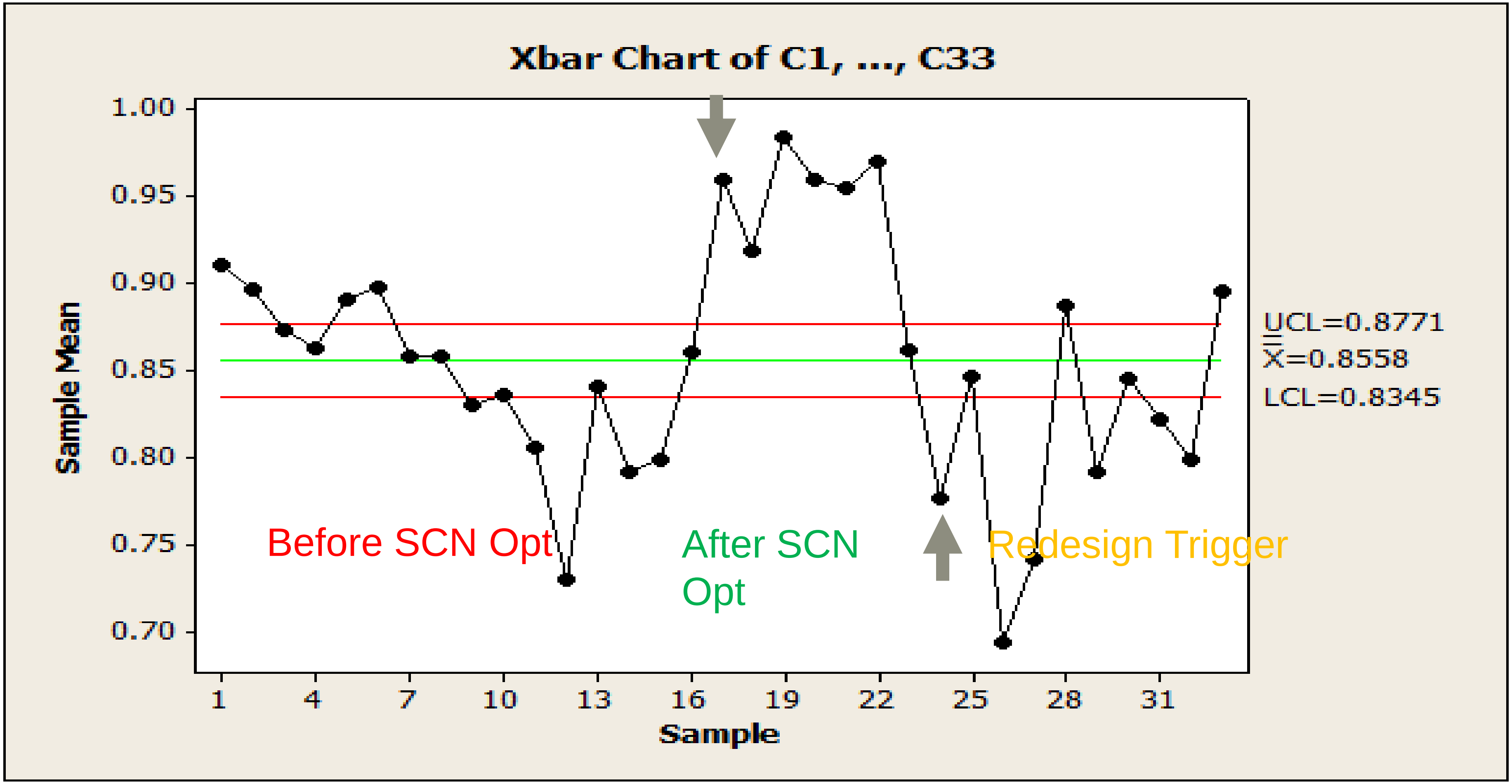
- The control limits for the range R chart are defined by:

- UCL $= D_4\bar{R}$

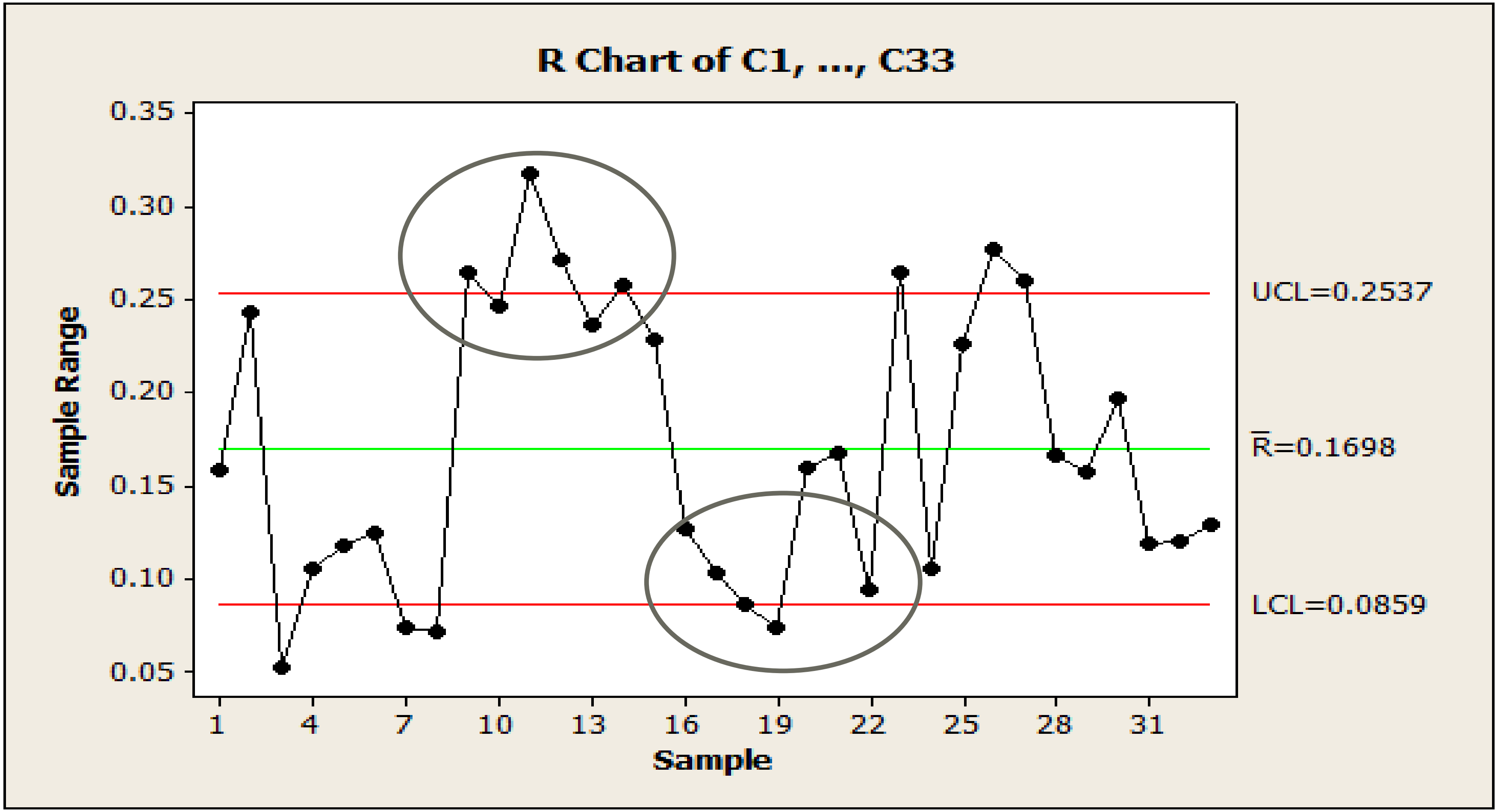
- LCL $= D_3\bar{R}$

- Where, D_4 and D_3 are table values obtained from standard quality control tables.

Supply Chain Network Cross Efficiency Results: $\bar{X}$ Chart



Supply Chain Network Cross Efficiency Results: R-Chart



Conclusions and Next Steps

- Case Company is using our approach as a dashboard system to monitor network efficiency

- Make the network assessment more comprehensive
  - Plant level data
  - Upstream data (suppliers)
  - Efficacy of Network DEA models
  - Big data and interactions between various supply chain partners