ROLL VARIABILITY ANALYSIS FOR NON-STATISTICIANS

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ABSTRACT

Roll variability can be characterized by several different methods. Off line cross-direction (CD) scans of thickness or coat weight give a snapshot of CD variation over a small machine-direction (MD) range. Roll hardness profiles have long been used to evaluate web uniformity in wound roll form - particularly for flagging potential web bagginess. Roll hardness profiles are easy to measure, but a strong correlation to roll quality depends on having a somewhat stable CD thickness or coat weight profile and relatively low MD or time variation.

Summary statistics from in-line scanning gauges (mean, range and standard deviation) sample the entire roll, but don't describe the distribution or location of the variation. 2D contour plots are helpful for visualizing roll variation, but alone aren't enough to translate that variation into a useful specification.

Since specification limits for good web processing are often much tighter than limits for good end use function, making the best use of scanning gauge data is helpful for efficiently focusing process improvement efforts. Analysis of Variance (ANOVA) is able to evaluate the uniformity of a web property (thickness, coat weight) from an inline scanning gauge and partition the roll variance in the MD and CD directions.

This paper shows how the combination of ANOVA, control charting, and contour plotting can be used to both quantify and visualize roll variability within and between rolls in order to drive web uniformity improvement.

NOMENCLATURE

ANOVA	Analysis of Variance
CD	Cross Machine Direction
MD	Machine Direction
I-MR-R/S	Individuals – Moving Range – Range or Standard Deviation
X-bar-R/S	Mean – Range or Standard Deviation
USL	Upper Spec Limit

LSL Lower Spec Limit

INTRODUCTION

Web uniformity impacts wound roll behavior and is critical for reducing defects like telescoping, bagginess, and curl. Excessive caliper or coat weight variation in the cross direction can encourage rolls to telescope or lanes of material to yield and become baggy leading to wrinkling in downstream processes. Moisture content non-uniformity can impact curl and also bagginess.

Caliper, coat weight and moisture are often measured in-line with sensors which scan the full width of the web and throughout the whole roll. This paper will not cover active control strategies for web uniformity or scanning sensor signal treatment but will focus on showing a straightforward approach for web process troubleshooters familiar with statistical software to analyze scanning gauge data.

Along with ANOVA to determine the significance of the variation, "Within and Between Subgroup" control charting (I-MR-S) is used to scale and quantify the CD and MD variation. I-MR-S charting is proposed over X-bar-S charting because it includes a measure of the variation between neighboring lanes – which is relevant for baggy lane development and profile control and also gives a more reasonable expectation for in-control conditions. Combining the control charts with contour plots helps to visualize the distribution of the variation in location and time to help focus variation reduction efforts.

Product specification limits are based on end use performance, not on processability so it's helpful to consider different levels of significance for control limits. Practical process specifications are typically tighter than end use product specifications – and are often closer to statistical control limits [1].

Levels of Significance

- Contractual – product specification, what is required for end use performance
- Practical – process specification, correlated to web defects like bagginess or telescoping
- Statistical – based on analysis, normal process variation

Web processes that meet the product end use requirements but struggle during running would benefit from determining practical process specifications by first figuring out statistical control limits, then correlating roll variation to defect frequency.

GAUGE DISPLAY

In-process data is often displayed as in Figure 1 where the last scan is displayed – or sometimes the average of the last few scans – which gives a short term view of CD variation. Overall roll statistics are often summarized by logging the gauge mean, range and standard deviation for the entire roll. Neither the last few scans nor the full roll statistics gives an idea of the distribution of the variation, the longer term trending or stability, or the relative magnitude of CD vs MD variation. Sometimes roll maps are used which give a picture of the distribution, but usually don't include enough statistical analysis to evaluate significance.

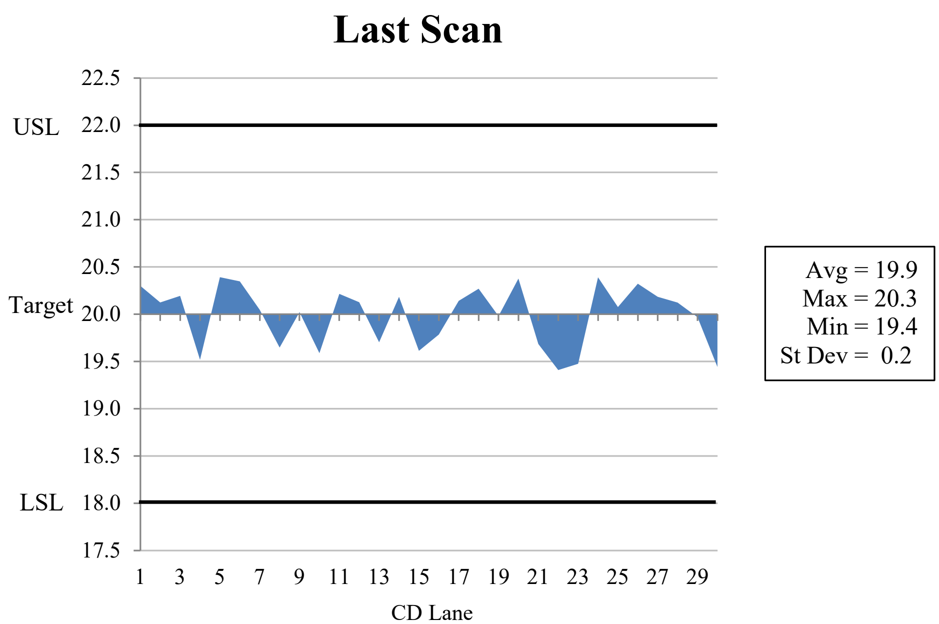

Figure 1 – Typical Scanning Gauge Display

MACHINE & CROSS MACHINE VARIATION

Roll hardness profiles, especially measured by newer instruments[1] which can measure hardness every 2.5 mm (0.1 inch), are very good at detecting small CD variation which has built up over thousands of layers. These instruments depend on CD variation patterns persisting throughout the roll. But analyzing scan data after the rolls are made can show if the CD profile changed throughout the roll with time.

The MD variation looked at here is "trending over time" not higher frequency variation which requires more sophisticated techniques to identify.

DATA SAMPLING

Scanning gauges move across the web width and sample the web in a zigzag pattern (Figure 2). The diagonal path is a factor for short term MD and CD variation for active profile control systems but is not a problem for 2D analysis after the roll is made [2,3] when each measurement is tagged with CD lane position and either a time stamp for the scan or the roll length.

[1] For example, ACA RoQ or Tapio RQP

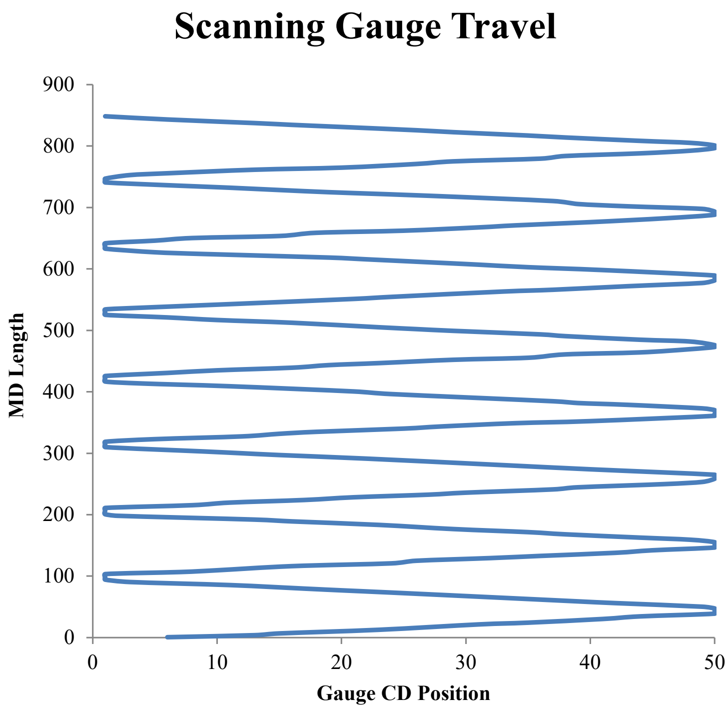

Figure 2 – Scanning Gauge Travel

Gauge readings are averaged over a window (data box) as determined by scan speed, web width and number of lanes desired (Figure 3). The width of the data box is web width/number of lanes. The length of the data box is the width times the ratio of the line speed to the scan speed {1}. The length of data box can be 1000 times its width.

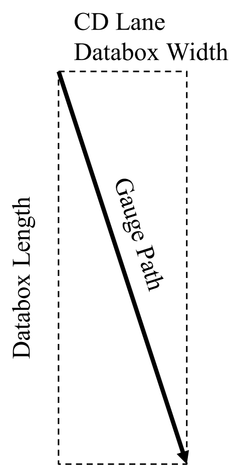

Figure 3 – Databox Dimensions

$$DataboxLength = DataboxWidth \frac{LineSpeed}{ScanSpeed} \tag{1}$$

Data Logging

Scan data is often logged as an array with time stamps as row names and CD lanes as columns. Another way is into three columns: roll length, CD lane, and gauge measurement. Analysis examples using both are included. When data is available for multiple rolls, including another column for either option which gives roll ID is helpful for analyzing between-roll variation.

OVERVIEW OF ANALYSIS TECHNIQUE

The two analysis examples that follow use Minitab, but any software for calculating ANOVA, plotting control charts and creating contour plots can be used. Below is a list of the statistical tools used.

1. ANOVA for checking statistical significance of MD and CD variation
2. Contour plot for visualizing 2D variation
3. I-MR-R/S MD control chart for evaluating trending over time
4. Crop data if necessary for MD stability for CD analysis
5. I-MR-R/S CD control chart for CD variation
6. Characterize normal MD and CD variation limits – compare profiles
7. Combine control charts with contour plot

EXAMPLE 1

Coat Weight for 3 Rolls: 29 CD Lanes, 95 scans

The coat weight data for the first example covers an array of 2755 measurements arranged as 95 scans (rows) over 29 CD lanes (columns). See Table 1.

Roll	Scan	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	…	L29	Scan AVG
A	1	20.0	19.4	19.7	19.9	20.3	20.9	21.3	21.9	22.5	22.4	21.8	21.8	21.9	22.0		16.6	20.8
A	2	19.5	19.2	19.5	19.7	20.4	20.8	21.2	21.9	22.3	22.0	21.6	21.6	21.7	21.9		16.4	20.6
A	3	19.7	19.3	19.6	19.8	20.4	20.8	21.1	21.8	22.1	21.8	21.5	21.6	21.6	21.7		17.3	20.7
A	4	20.0	19.7	20.1	20.2	20.6	20.8	21.0	21.5	21.7	21.3	21.0	21.2	21.5	21.6		17.4	20.6
A	5	20.3	19.8	20.1	20.1	20.5	20.8	21.0	21.4	21.7	21.4	21.0	21.1	21.1	21.4		17.9	20.6
A	6	20.6	19.9	20.1	20.2	20.4	20.7	20.9	21.3	21.7	21.5	21.1	21.0	21.1	21.2		17.9	20.6
A	7	20.7	20.0	20.1	20.2	20.4	20.8	20.9	21.2	21.6	21.5	21.1	21.0	21.2	21.2		18.0	20.6
A	8	20.5	20.0	20.2	20.2	20.6	20.8	21.0	21.4	21.7	21.4	21.1	21.1	21.1	21.1		18.1	20.6
A	9	20.7	20.3	20.4	20.3	20.7	20.8	20.9	21.2	21.5	21.3	20.9	21.0	21.0	21.0		18.2	20.6
A	10	20.7	20.3	20.4	20.3	20.6	20.8	20.8	21.2	21.4	21.1	20.9	21.0	21.0	20.9		18.3	20.5
A	11	20.9	20.2	20.4	20.4	20.5	20.7	20.6	21.0	21.2	21.1	20.7	20.8	20.9	20.9		18.4	20.5
A	12	21.2	20.5	20.6	20.6	20.7	20.9	20.9	21.0	21.3	21.2	20.9	21.0	21.0	20.9		18.5	20.7
A	13	20.9	20.4	20.5	20.4	20.5	20.7	20.6	20.8	21.0	20.9	20.7	20.7	20.8	20.8		18.6	20.5
A	14	21.0	20.5	20.6	20.5	20.5	20.7	20.7	20.7	20.9	20.8	20.6	20.7	20.8	20.7		19.1	20.5
A	15	20.7	20.3	20.5	20.4	20.6	20.7	20.7	20.8	21.1	20.9	20.7	20.9	20.9	20.9		18.6	20.4
A	16	20.9	20.4	20.6	20.5	20.6	20.8	20.9	20.9	21.1	21.1	20.7	20.8	21.0	21.0		19.3	20.8
A	17	21.3	20.7	20.8	20.7	20.8	21.0	20.8	20.9	21.0	21.0	20.8	20.9	21.0	21.0		19.5	20.7
	⋮																⋮	
C	95	20.8	20.7	20.8	20.8	20.8	20.9	20.8	20.8	20.8	20.8	20.7	20.8	20.8	20.8	…	20.05	
Lane AVG		20.9	20.6	20.7	20.6	20.7	20.8	20.7	20.8	20.8	20.8	20.7	20.8	20.8	20.8			

Overall AVG	Min	Max	Stdev
20.7	16.4	22.5	0.43

Table 1 – Coat Weight Data for Example 1

ANOVA

For analysis in Minitab, the columns above are stacked[2] to make four columns: Roll, Scan, Lane and Coat Weight. The results of an ANOVA are shown in Table 2. Both CD (Lane) and MD (Scan) are statistically significant since the P-values are less than 0.05.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Lane	28	75.91	2.7111	17.37	***0.000***
Scan	94	18.83	0.2003	1.28	***0.037***
Error	2632	410.88	0.1561		
Total	2754	505.62			

Table 2 – ANOVA for Example 1

Contour Plotting

The contour plot in Figure 4 shows both CD and MD variation in the first 20 scans but mostly CD variation in the later scans.

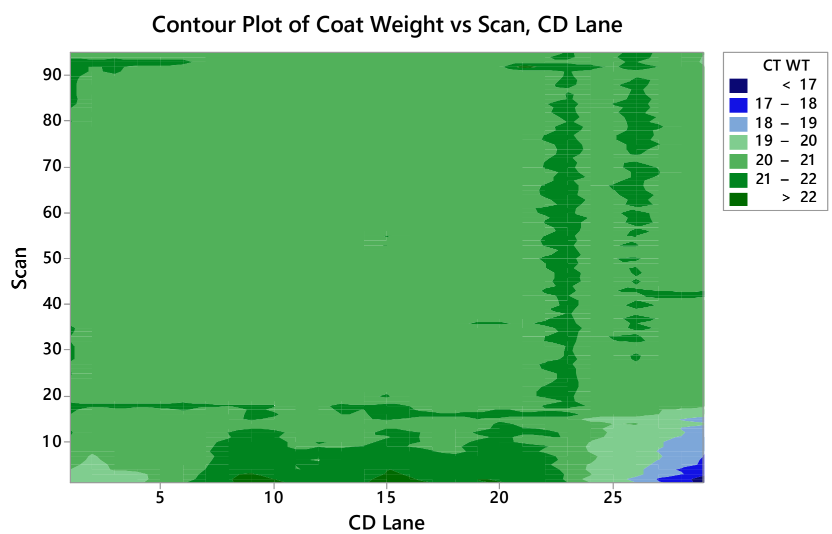

Figure 4 – Contour Plot of Coat Weight

Control Charting-MD & CD

Figure 5 shows the Individuals – Moving Range – Standard Deviation chart subgrouping the data by scan and staged by Roll. It shows that there was much more variation with time for Roll A than for Rolls B & C. (Roll A was a start-up roll.)

Describing the three part I-MR-S chart from the bottom up:

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[2] "Data>Stack> Columns" and "Calc>Make Patterned Data>Simple Set of Numbers" in Minitab simplify this step.

- Scan StDev – standard deviation of each scan shows the variation across the width for each scan
- MR of Scan Mean – Moving range shows difference between each pair of scans – and shows the volatility with time
- Scan Mean – average coat weight for each scan. The control limits are based on the average moving range (MR-bar) instead of the Scan StDev (within scan or CD variation) used for calculating control limits for an X-bar-S chart.

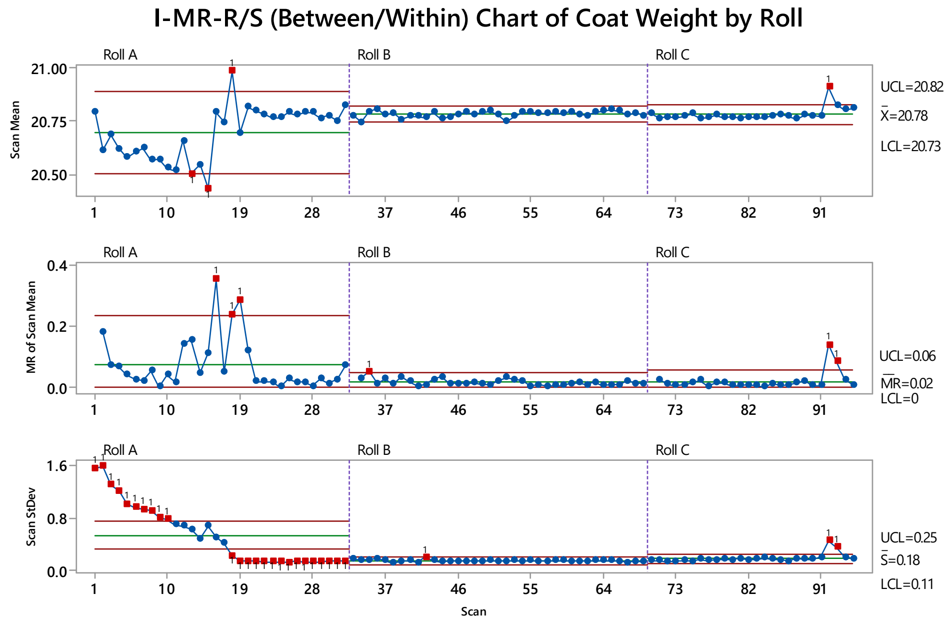

Figure 5 – Individuals and Moving Range and Standard Deviation Chart for Coat Weight

The objective for this type of 2D analysis is to understand the variation in the CD and MD separately. During steady state operation, CD variation it typically greater than MD variation. I-MR-S charts are normally used for changes over time (MD) – but there is also benefit to using them for CD variation in this type of analysis because short term jumps between lanes (which indicate potential bagginess) will be highlighted.

Using an X-bar-S chart for MD variation (subgrouping over scan) would have resulted in control limits too generous for characterizing typical MD variation – significant MD changes would not be detected. At the same time, using an X-bar-S chart for CD variation (subgrouping by lane) would have shown overly tight control limits for typical CD variation. Many lanes would look “out of control” when they really weren’t. Using I-MR-S charting for both directions results in more meaningful and appropriate control limits.

Since clearly Roll A is not under steady state conditions, to quantify the steady state MD and CD variation, the data from Rolls B & C only was used. Figure 6 shows the control chart for the CD variation of Rolls B and C by lane.

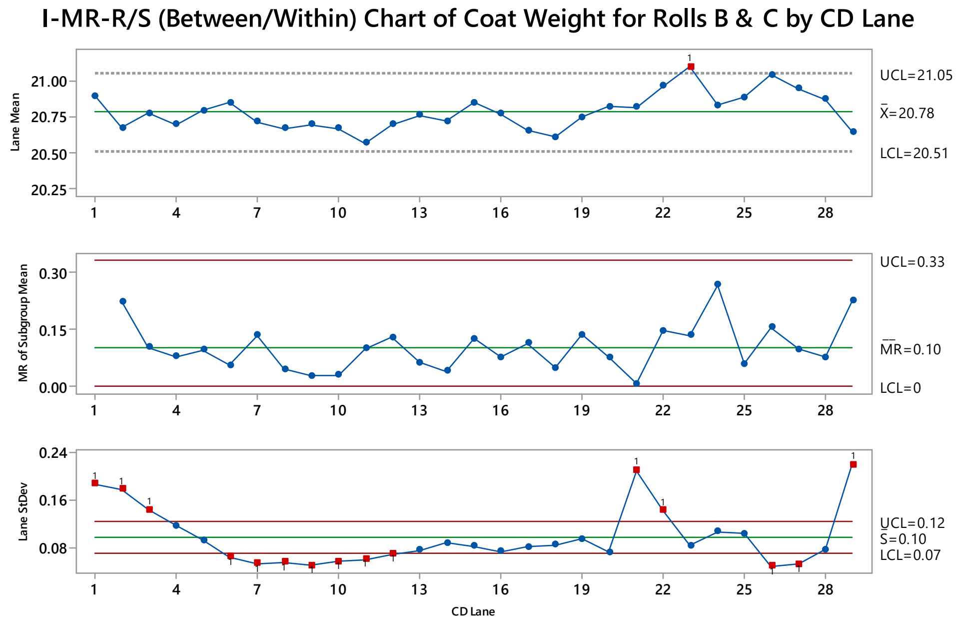

Figure 6 – Between & Within Lane variation for Rolls B&C

Table 3 shows the summary of statistics for each direction. The MD StDev (within CD lanes) is less than the CD StDev (within MD scans) because the CD variation is greater. However using the average moving range for each direction to calculate the respective control limits results in more reasonable limits which is easy to see in Figure 7.

	Overall	CD Lanes	MD Scans
Mean	20.7		
St Dev Within Subgroup	0.43	0.10	0.16
Control Limits Between Subgroup		±1.3%	±0.2%

Table 3 – Summary Statistics for MD & CD Control Charts

Figure 7 shows the MD scan averages with the control limits (dashed lines) from the I-MR-R/S charts on the left and the CD lane averages and control limits on the right. It shows the relative width of the control limits by direction and also highlights a few locations which are out of control. This is the same information which is wrapped around the contour plot in Figure 8.

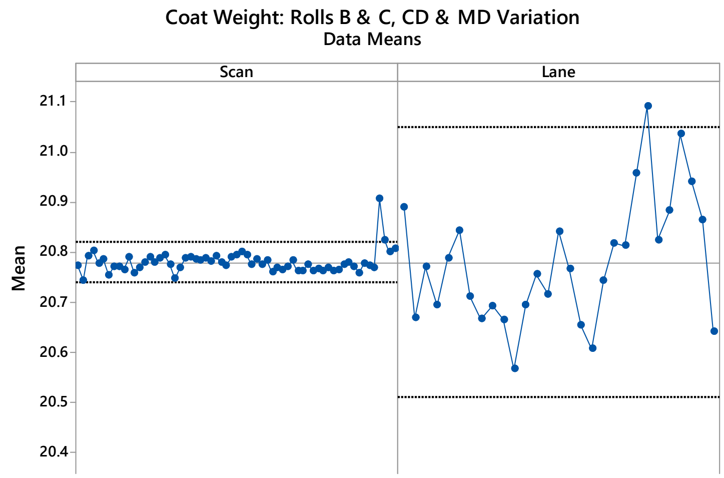

Figure 7 – Comparison of means and control limits for MD (Scan) and CD (Lane) variability

Contour Plot plus Control Charts

Combining a contour plot of Rolls B and C with the control charts[3] for MD and CD variation shows the distribution of steady state variation while quantifying the variation with control limits for each direction. See Figure 8. Lane 23 and Scan 92 show up in the contour plot as light areas and as points outside the upper control limits in the relevant charts.

[3] Only the Lane Mean and Scan Mean portions of the I-MR-S charts are shown for better visibility.

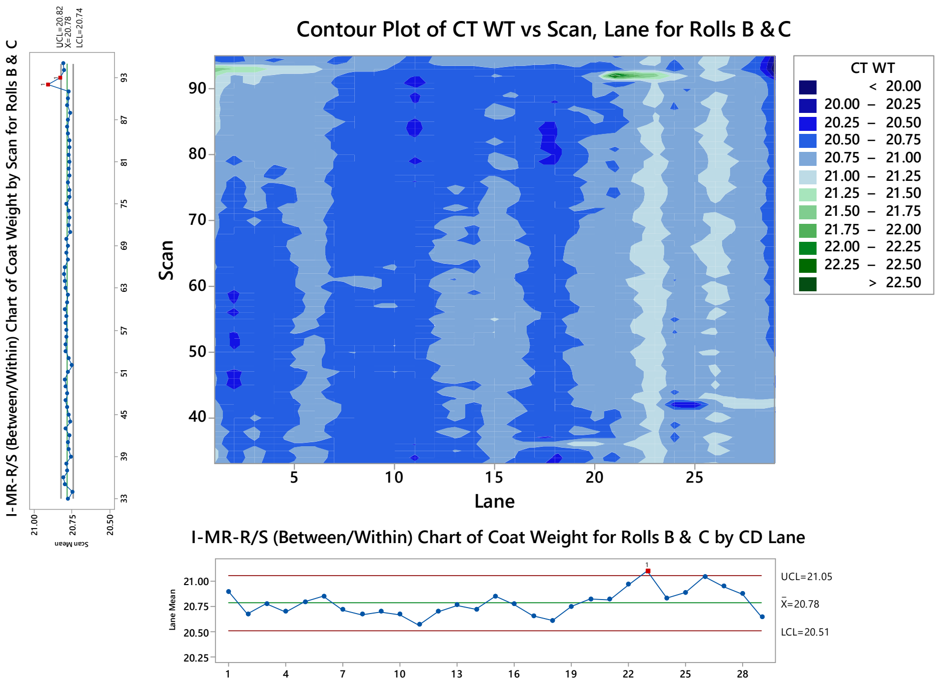

Figure 8 - Contour Plot and Lane & Scan Means charts for Rolls B & C Coat Weight

EXAMPLE 2

Thickness for 100 rolls, 50 lanes

The second example uses thickness data over 50 lanes for 100 consecutive rolls which includes over 100,000 measurements. Because the measurements were logged by roll length and to get a high level view of the variation with time, the MD variation was analyzed by Roll rather than by scan as in the previous example.

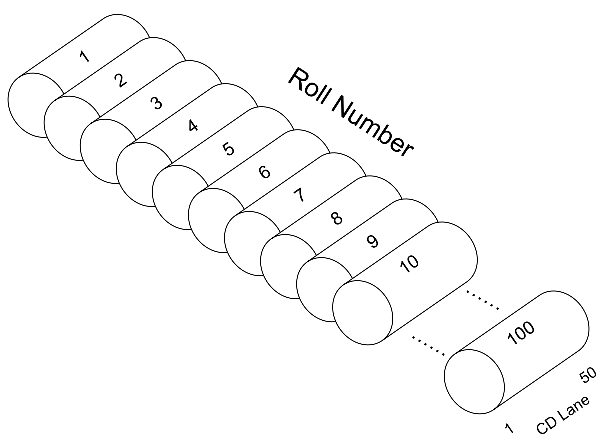

Figure 9 – Data Source for Example 2

Roll	Cumulative Length	CD Lane	Thickness
1	1	6	100.56
1	4	13	99.96
1	7	15	101.52
1	13	23	101.16
1	21	31	100.32
1	24	35	99.60
1	30	41	100.80
1	34	44	100.32
1	39	50	100.80
1	43	50	102.72
1	47	50	102.96
1	50	49	103.08
1	56	42	101.52
1	59	39	102.00
1	65	33	101.88
1	73	24	101.52
⋮			⋮
100	490,645	11	101.04

Avg	101.84
StDev	1.99
Min	93.00
Max	111.12

Table 4 – Thickness Data for Example 2

ANOVA

The ANOVA for Example 2 shows that both Roll and CD Lane are statistically significant – Table 5.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Roll**	99	35538	358.97	126.30	***0.000***
CD Lane	49	77397	1579.54	555.72	***0.000***
Error	100956	286949	2.84		
Lack-of-Fit	4844	61740	12.75	5.44	0.000
Pure Error	96112	225209	2.34		
Total	101104	399320			

Table 5 – ANOVA for Example 2

Contour Plot

The contour plot in Figure 9 shows areas of lower thickness around Roll 65 and higher thickness at the edges.

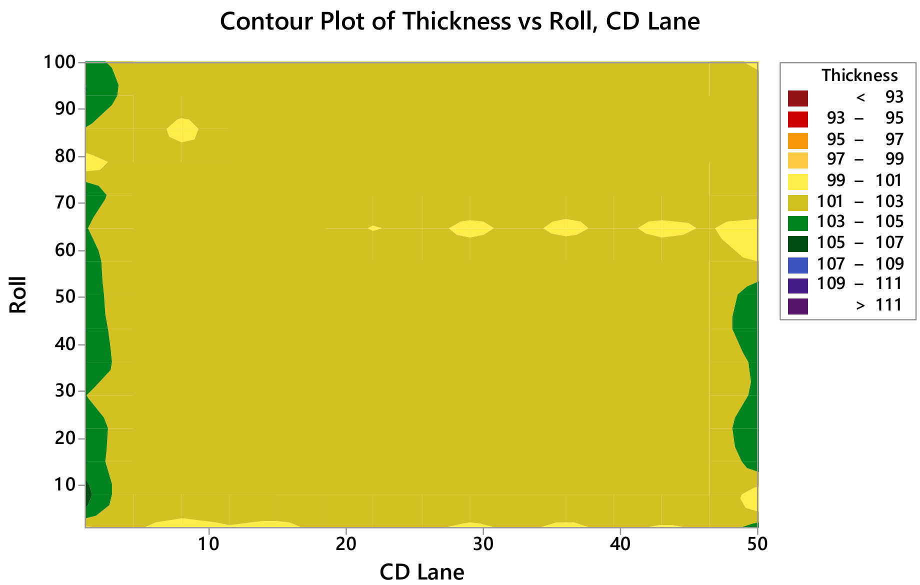

Figure 9 – Contour Plot of Thickness for Example 2

Control Charting – MD & CD

Figures 10 and 11 show the I-MR-S charts for thickness by Roll (MD) and Lane (CD).

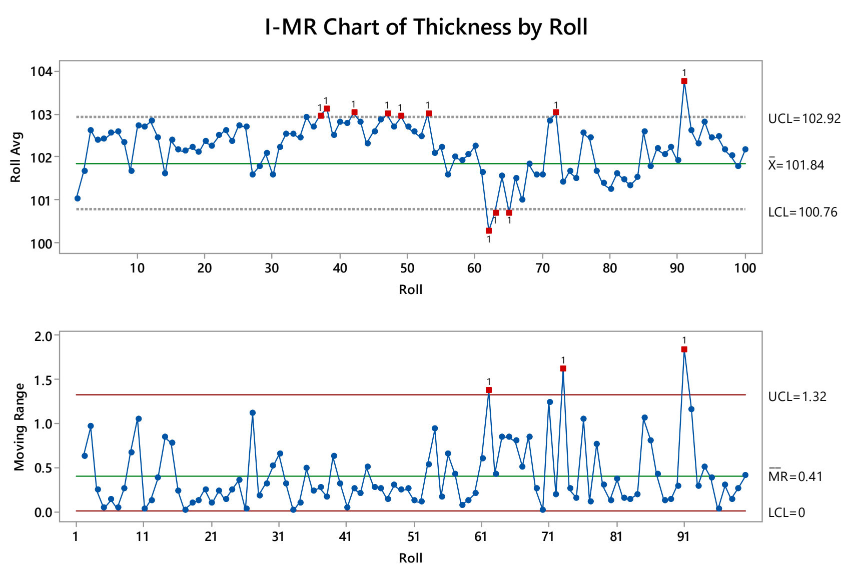

Figure 10- Individuals and Moving Range for Thickness by Roll (MD)

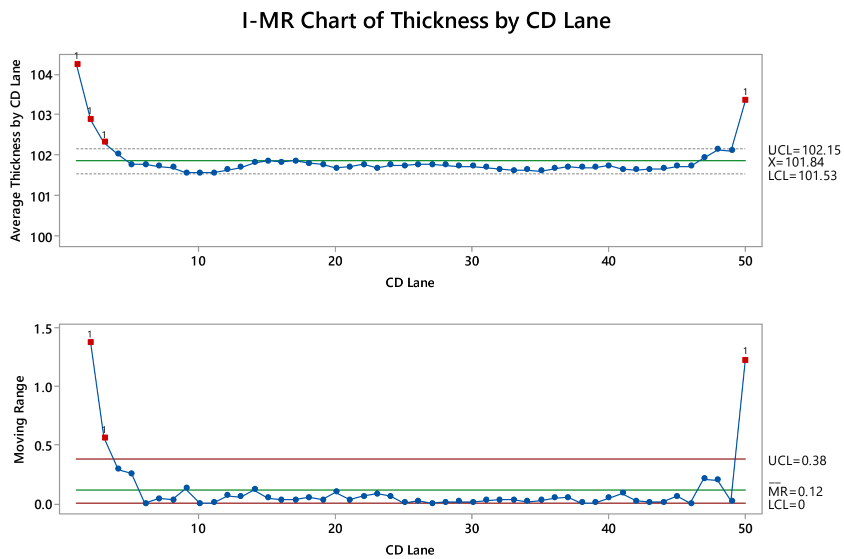

Figure 11 – Individuals and Moving Range for Thickness by Lane (CD)

Table 6 shows the summary statistics for Example 2. The CD variation is relatively small for most of the width with most of the variation showing up at the edges – which were often baggy. This example with data collected for over 450K meters showed a statistically significant difference at the edges – which because it was only about 2.5% higher the mean, might not have gotten attention if not analyzed in this way.

	Overall	CD Lanes	MD Rolls
Mean	101.84		
St Dev Within Subgroup	1.99	1.87	1.28
Control Limits Between Subgroup		±0.3%	±1.1%

Table 6 – Summary Statistics for Thickness for Example 2

The side-by-side chart in Figure 12 shows the persistent CD pattern. The MD variation is curious and begs for more analysis at a closer level to see what changes over a shorter time scale are happening-over say 10 rolls rather than 100.

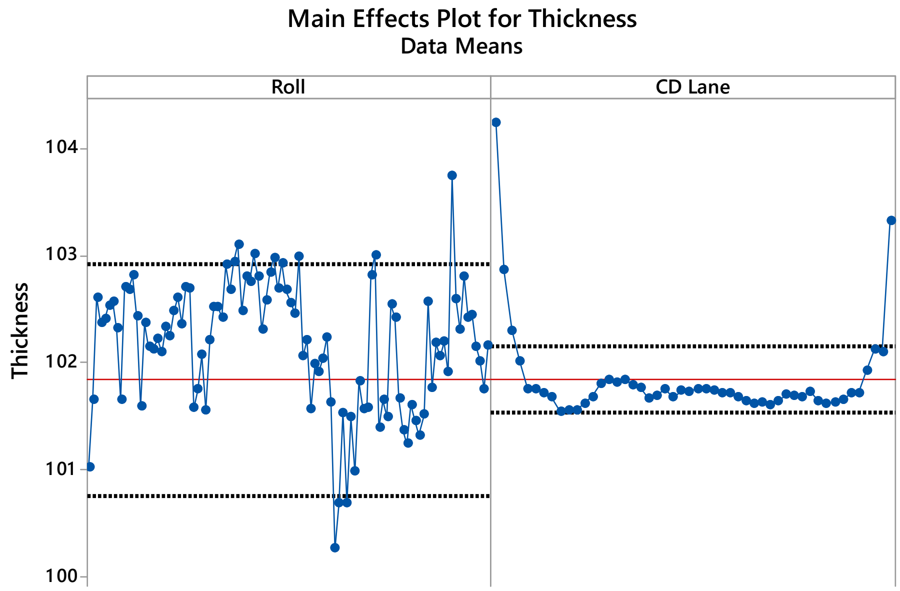

Figure 12 - Comparison of means and control limits for MD and CD variability

Contour Plot Plus Control Charts

Figure 13 shows the contour plot combined with the control charts.

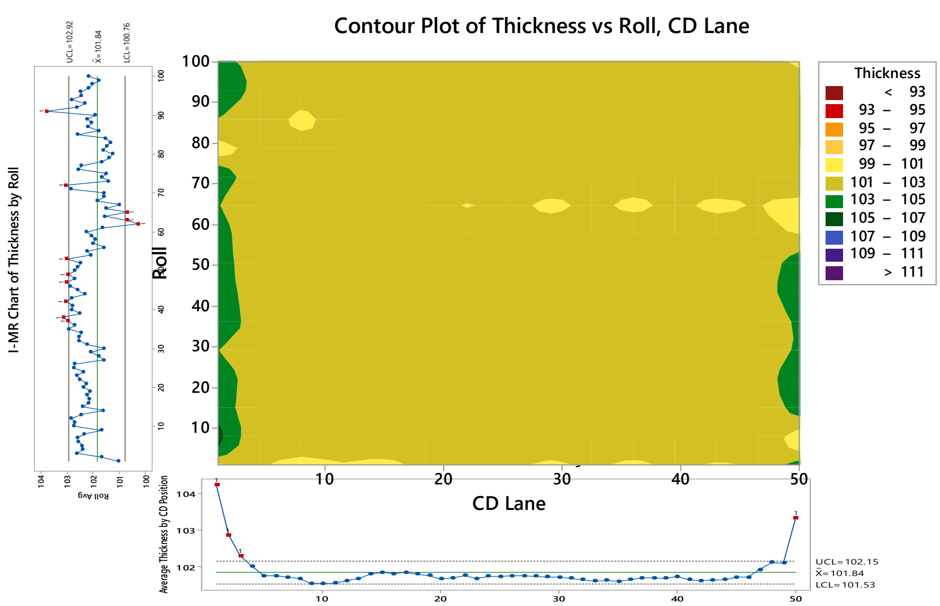

Figure 13-Contour Plot and Lane & Roll Means charts for Thickness

SUMMARY

Variation between and within rolls can be quantified, visualized and located by applying basic statistical software (ANOVA and I-MR-S charting) in combination with contour plotting to scanning gauge measurements. Once excessive variation is pinned down to particular CD locations or timing in the web process, then efforts to reduce variation can be focused and prioritized. The technique described here is helpful for troubleshooting and is an important early step for correlating process parameters to web defects like roll telescoping, baggy web and curl.

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