Industrial Quality Improvement – an Historic Example

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Abstract

A long time ago in a galaxy far far away…

Actually, it was 1986 in Rochester, NY. Eastman Kodak had 60,000 employees in the community. Sales of photographic film (that stuff your grandparents used to take pictures before digital cameras) were expanding. Waste was too high and the product was too variable. After trying everything else, the corporate quality council finally obtained a green light for a statistical process control program. Within 4 years, the variance for several key measures dropped by a factor of 100. Products that had averaged 6 formula changes per event went for 6 months without a change.

Photographic film manufacturing is no longer important for most of us, but the quality improvement processes used are as relevant today as ever. They are also enabled by JMP. In 1986 we used pencil and paper and mainframe SAS. Data collection sheets, cause and effect diagrams, regression analysis, and SPC charts are all facilitated today by JMP.

Background

The corporate quality council at Kodak had known for years that we needed a robust statistical process control (SPC) program. They were “persuaded” by upper management to pursue less costly programs such as slogan contests and pep rallies. (You can imagine how well those slogans and pep rallies worked.) By 1986 with product waste hitting new records, they finally got the funding to embark on SPC.

Silver-based photographic film has largely been replaced by digital sensors. The main reason for choosing this subject is the author’s familiarity with it. The improvement process described here was a small part of the overall effort.

Topics

- Basic process
- Known Effects
- Data Sheets
- Cause and Effect Diagrams
- Trend Charts
- Statistical Process Control (SPC) and the people side of SPC

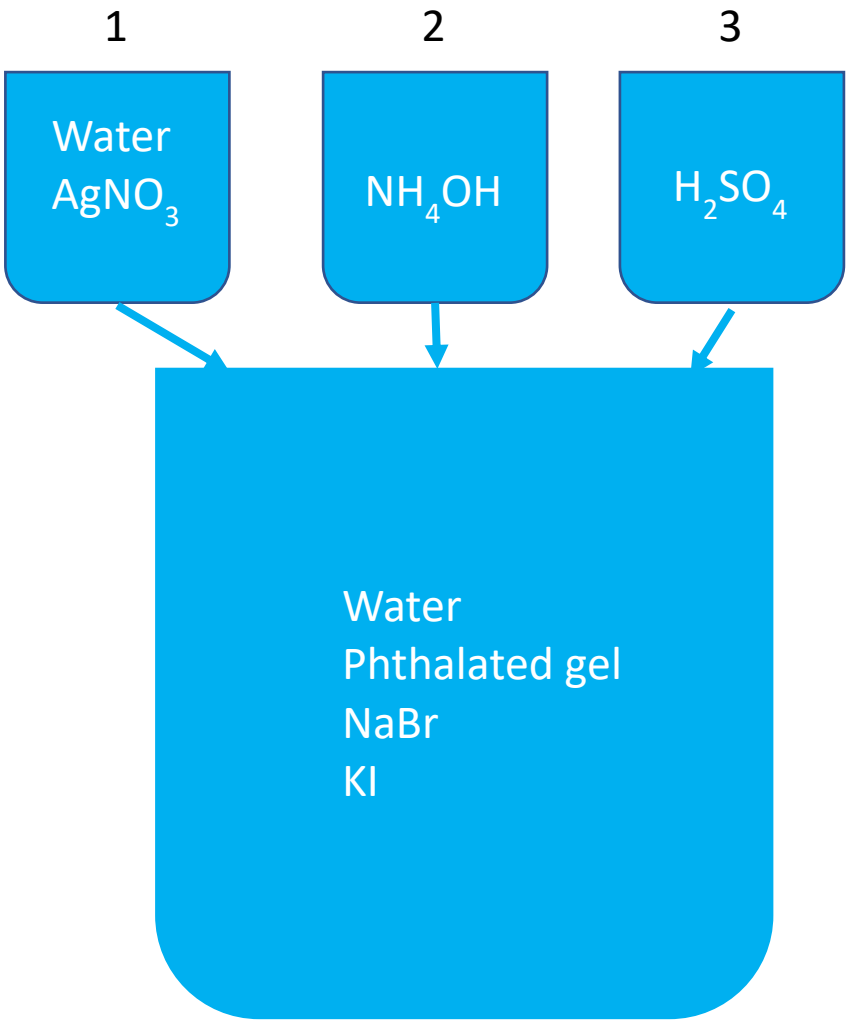
- How do you do SPC when you make 6 batches/year?

Basic Process: High-level View of Photographic film Manufacturing

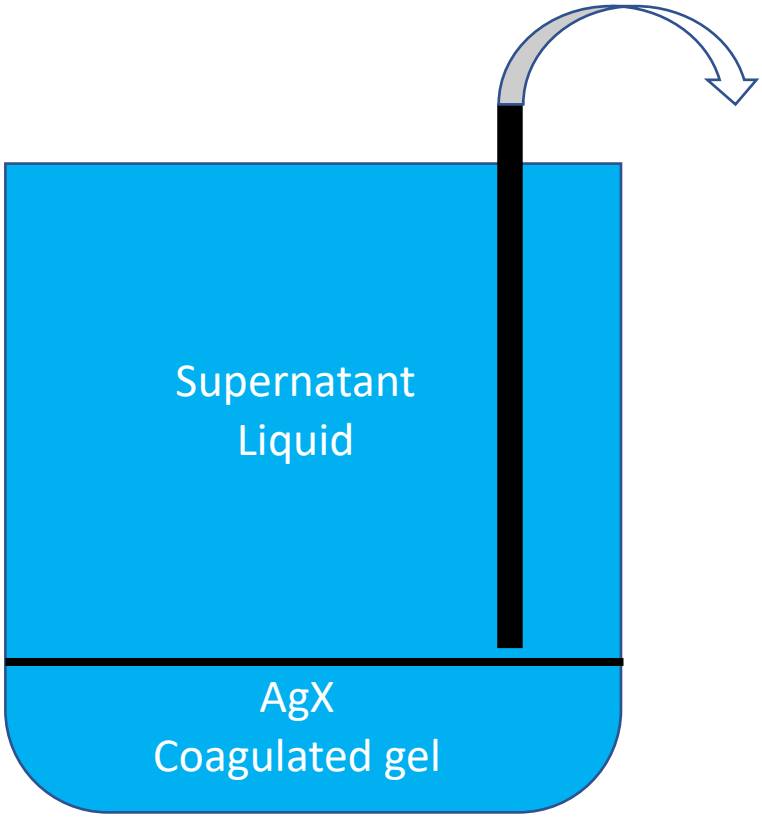
- Weigh out ingredients
- Precipitate silver halide (AgX) “emulsions”
- Wash emulsions
- Sensitize samples of emulsions at 3 different temperatures and choose the best one
- Sensitize emulsions at the chosen temperature
- Assemble all ingredients and test multiple parameters for each layer
- Make corrections for layers out of spec
- Coat a short pilot and test
- Adjust formulas
- Coat a short re-pilot and test
- Adjust formulas
- Coat remaining emulsions in 1 or 2 large coating runs and test
- If necessary, take the coated rolls back to the coating ally and apply filter dyes to correct color balance

The underlined points are all accommodation steps that were routinely required because we couldn’t get it right the first time.

Emulsion Manufacturing Process



Open kettles with steam jackets for temperature control and prop stirring were used. The main kettle started with water, phthallated gel, sodium bromide, and potassium iodide. Three jars above the kettle hold silver nitrate, ammonium hydroxide, and sulfuric acid. In the precipitation step, the silver nitrate solution flows through calibrated disc orifices for flow control. In the growth step, ammonium hydroxide was added. This dissolves the small crystals and deposits the material on the larger grains.



To wash out the nitrate, sodium, and potassium ions. Acid is added to coagulate the gel. The supernatant liquid is drawn off with a siphon.

Known Effects

Grain size and fog are two major properties of photographic emulsions that must be controlled. Grain size is affected by the initial flow rate of silver, the temperature, and the amount of ammonia used. The flow rate of silver is measured by recording the time it takes to empty the silver jar. Fog is the result when a silver halide crystal develops without being exposed to light. The free ionic silver concentration and the temperature have the largest impacts on fog. With a Ksp of 5×10^{-13} for AgBr, the free ionic silver concentration is extremely low, but it still has an impact on fog. The concentration is estimated by measuring the electrical potential when a silver electrode is placed in the liquid. This is referred to as vAg.

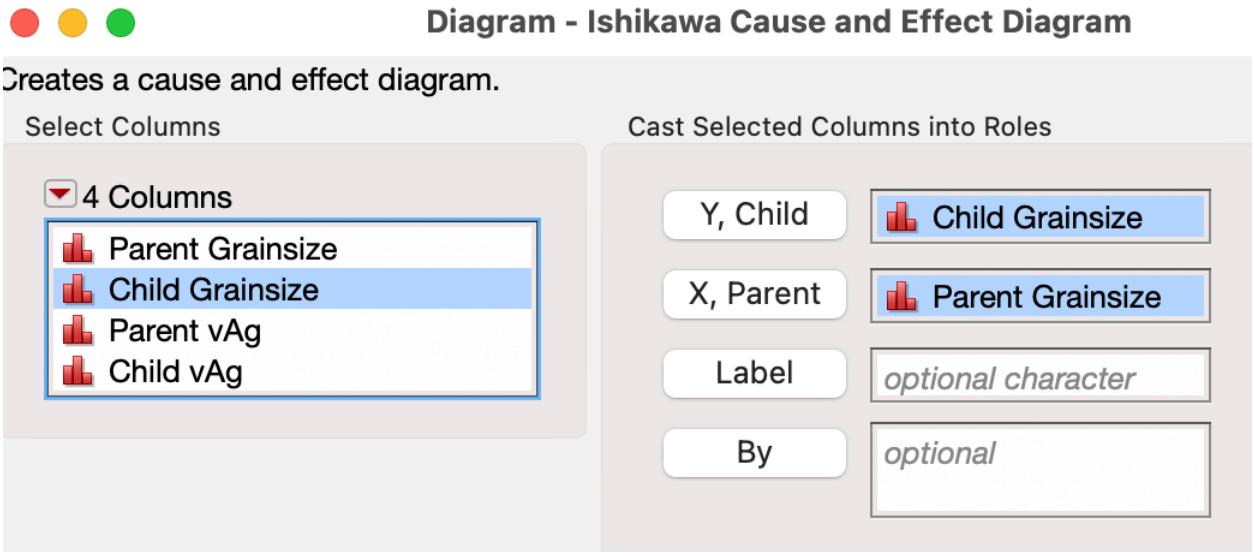
Cause and Effect Diagrams

In 1986 cause and effect diagrams were drawn by hand. Today this can easily be accomplished by entering all possible factors into a JMP data table. This example covers grain size and vAg.

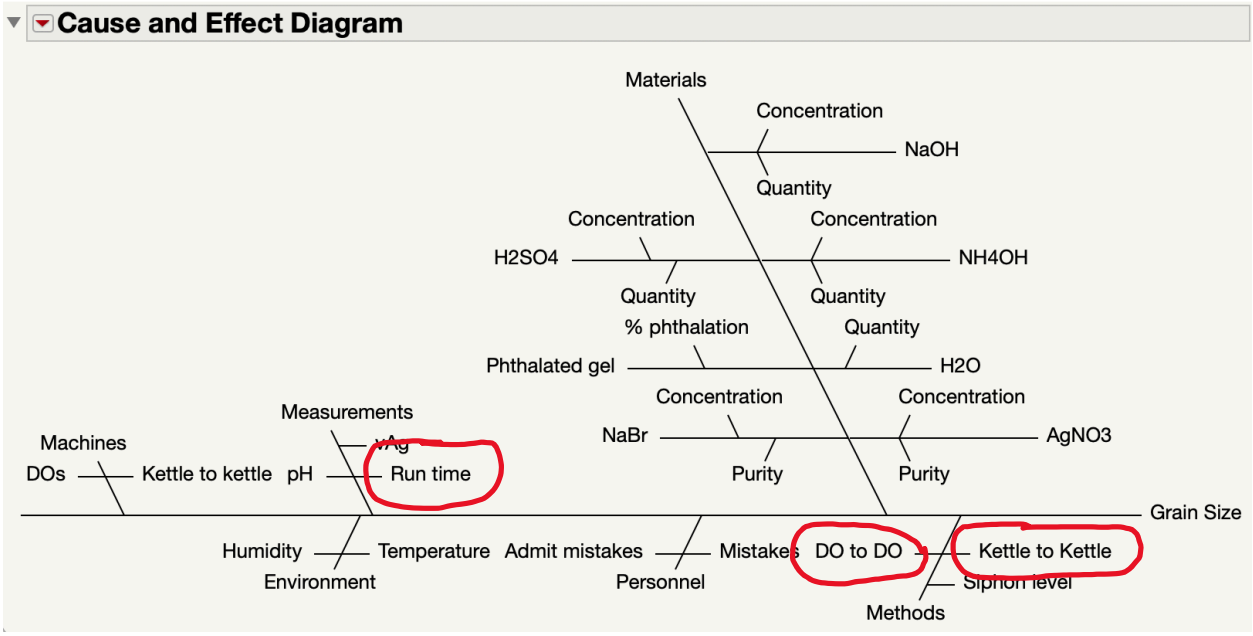
Fishbone

	Parent Grains...	Child Grain...	Parent vAg	Child vAg
1	Grain Size	Materials	vAg	Materials
2	Grain Size	Methods	vAg	Methods
3	Grain Size	Measurements	vAg	Measurements
4	Grain Size	Personnel	vAg	Personnel
5	Grain Size	Machines	vAg	Machines
6	Grain Size	Environment	vAg	Environment
7	Materials	AgNO3	Materials	AgNO3
8	Materials	NaBr	Materials	NaBr
9	Materials	H2O	Materials	H2O
10	Materials	Phthalated gel	Materials	Phthalated gel
11	Materials	NH4OH	Materials	NH4OH
12	Materials	H2SO4	Materials	H2SO4
13	Materials	NaOH	Materials	NaOH
14	Methods	Kettle to Kettle	Methods	Kettle to Kettle
15	Methods	DO to DO	Methods	DO to DO
16	AgNO3	Concentration	AgNO3	Concentration
17	AgNO3	Purity	AgNO3	Purity
18	NaBr	Concentration	NaBr	Concentration
19	NaBr	Purity	NaBr	Purity
20	H2O	Quantity	H2O	Quantity
21	Phthalated gel	% phthalation	Phthalated gel	% phthalation
22	NH4OH	Concentration	NH4OH	Concentration
23	NH4OH	Quantity	NH4OH	Quantity
24	H2SO4	Concentration	H2SO4	Concentration
25	H2SO4	Quantity	H2SO4	Quantity
26	NaOH	Concentration	NaOH	Concentration
27	NaOH	Quantity	NaOH	Quantity
28	Methods	Siphon level	Methods	Siphon level
29	Measurements	Run time	Measurements	Run time
30	Measurements	pH	Measurements	pH
31	Measurements	vAg	Personnel	Mistakes
32	Personnel	Mistakes	Personnel	Admit mista...
33	Personnel	Admit mistakes	Machines	Kettle to kettle
34	Machines	Kettle to kettle	Machines	DOs
35	Machines	DOs	Environment	Temperature
36	Environment	Temperature	Environment	Humidity
37	Environment	Humidity		

To construct the cause-and-effect diagram go to Analyze > Quality and Process > Diagram and identify the parent and child columns.

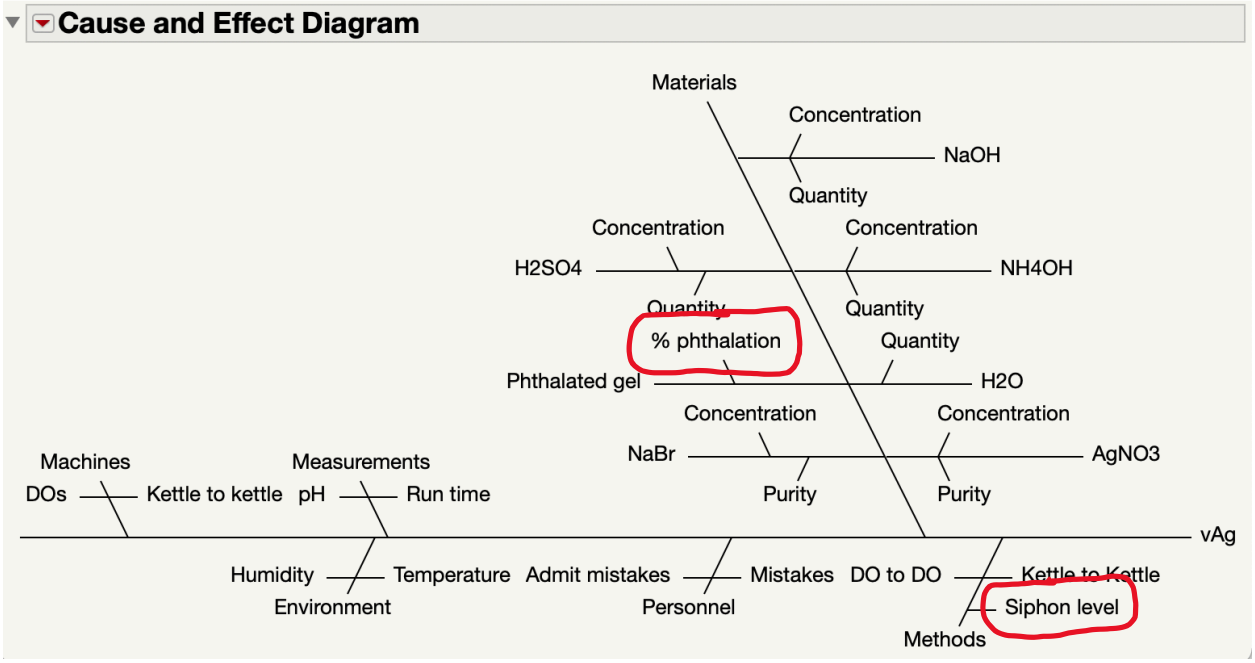


Click “OK” to generate the chart.



The three circled items were found to have the largest impact.

This is a similar chart for vAg.



Operators had been taught to siphon as much supernatant liquid as possible. The coagulated gel had variable density. It was better to siphon to a standard level than to siphon as much as possible

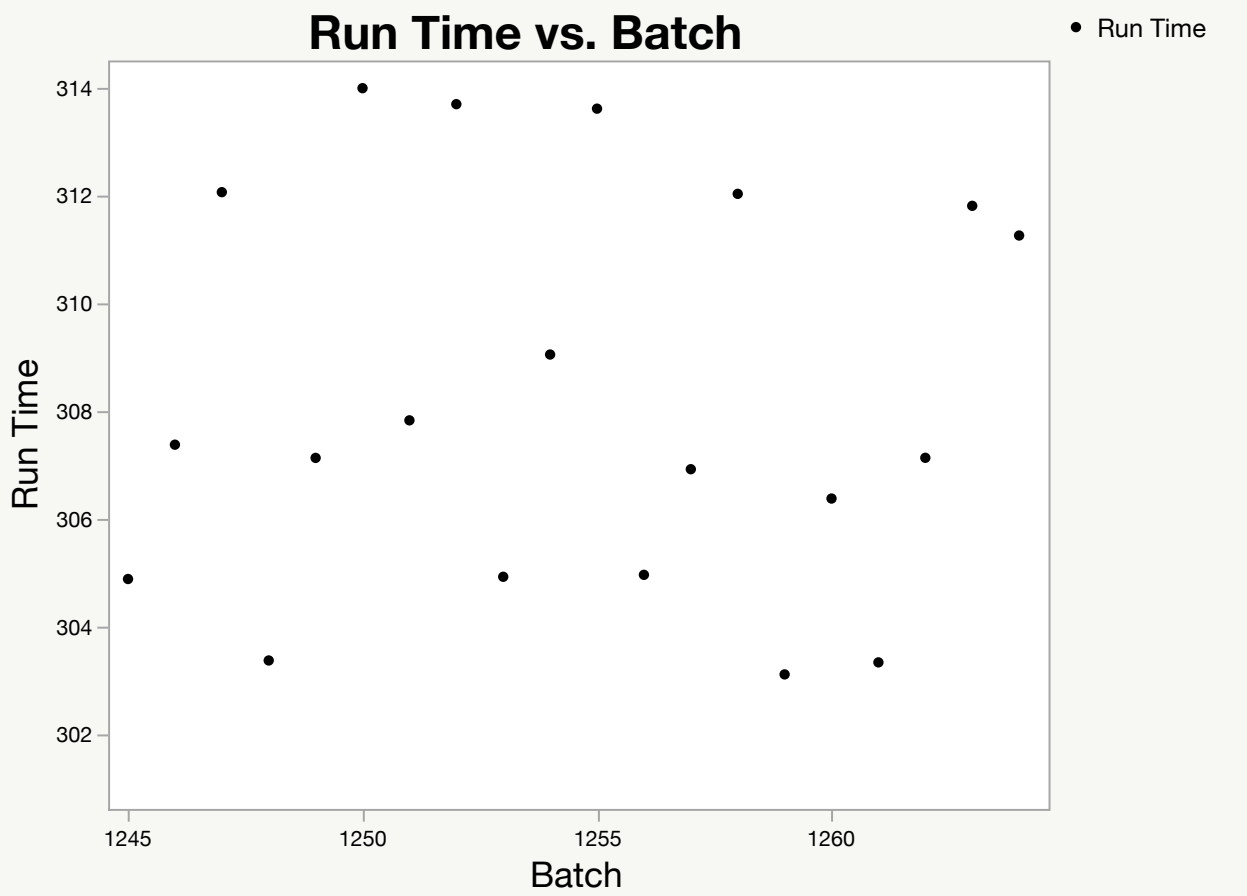
Data Sheets

The existing data sheets were kept in 14x17 ledger books. They contained years of hand-entered data on hundreds of emulsion kinds. They were kept in a lab that was only accessible by traversing dark hallways. We borrowed pages from the books and transcribed the data into SAS datasets. If JMP had been available, they would look like this.

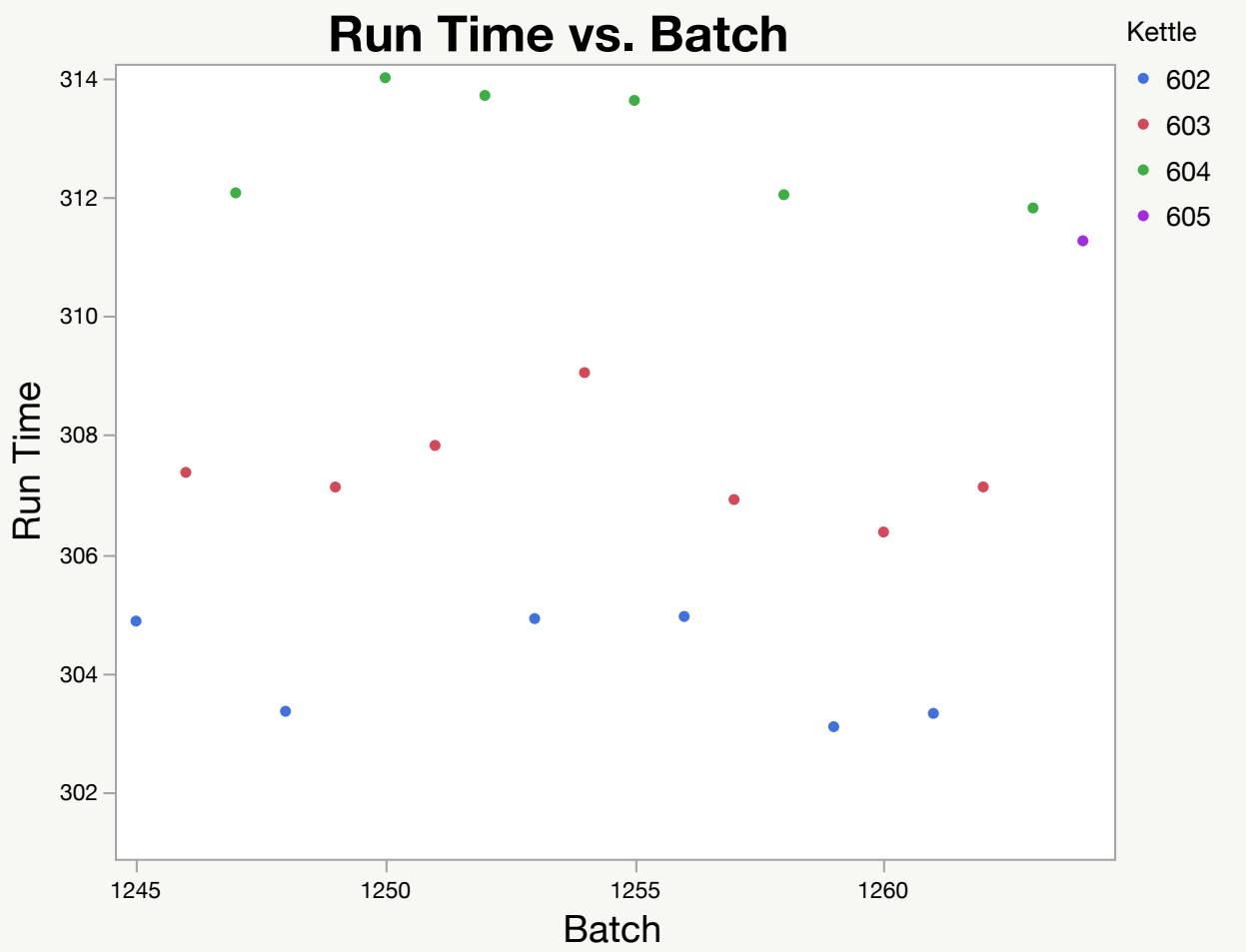
	Kind	Batch	Date	Kettle	Run Time	pH after NH4OH	pH after H2SO4	pH after NaOH	vAg
1	6001	1245	10Jun1986	602	305	13.23	4.28	5.44	1.65
2	6001	1246	10Jun1986	603	307	13.26	4.19	5.15	1.51
3	6001	1247	10Jun1986	604	312	13.28	4.18	5.63	1.36
4	6001	1248	29Jul1986	602	303	13.25	4.25	5.49	1.82
5	6001	1249	29Jul1986	603	307	13.27	4.26	5.11	1.51
6	6001	1250	29Jul1986	604	314	13.25	4.23	5.66	1.50
7	6001	1251	09Sep1986	603	308	13.23	4.23	5.89	1.73
8	6001	1252	09Sep1986	604	314	13.31	4.26	5.28	1.62
9	6001	1253	02Oct1986	602	305	13.22	4.26	5.63	1.45
10	6001	1254	02Oct1986	603	309	13.27	4.19	5.24	1.49
11	6001	1255	02Oct1986	604	314	13.24	4.27	5.45	1.87
12	6001	1256	11Nov1986	602	305	13.33	3.47	4.21	1.84
13	6001	1257	11Nov1986	603	307	13.21	4.23	5.58	1.54
14	6001	1258	11Nov1986	604	312	13.24	4.30	5.18	1.79
15	6001	1259	30Jan1987	602	303	13.28	4.26	5.33	1.37
16	6001	1260	30Jan1987	603	306	13.29	4.19	5.57	1.77
17	6001	1261	10Mar1987	602	303	13.24	4.25	5.59	1.74
18	6001	1262	10Mar1987	603	307	13.26	4.19	5.69	1.70
19	6001	1263	10Mar1987	604	312	13.29	4.35	5.62	1.59
20	6001	1264	10Mar1987	605	311	13.28	4.18	5.74	1.49

Trend Charts

This was an early trend chart for the silver runtime on one emulsion kind.



After identifying the kettle used for each batch, we quickly identified a key source of variability.



Gravity flow can be more repeatable than any pump if dimensions are kept consistent. The kettles were clearly different. Each emulsion kind was restricted to a single kettle.

Control charts

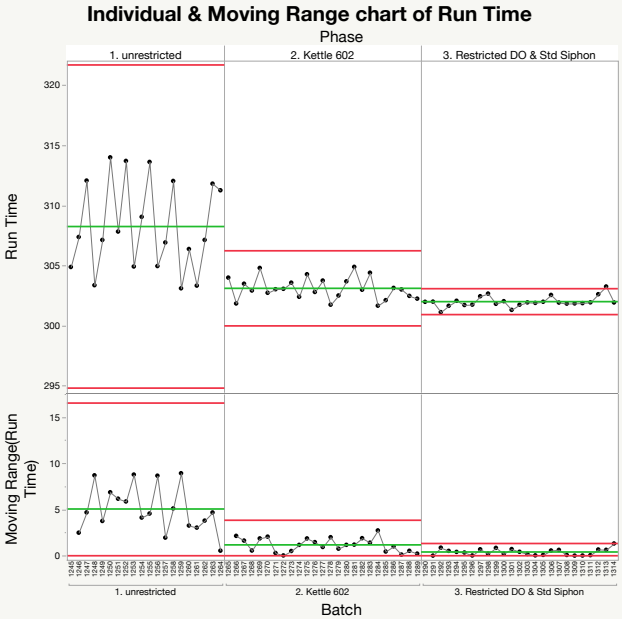
We started paying more attention to the people side of quality improvement. Several deviations from control chart orthodoxy were chosen to keep control charts simple so that operators could quickly learn how to construct and interpret them.

- Adopted plots of individuals without the moving range plot.
- Control limits were based on the standard deviation of the first 30 data points.
- Only two run rules were used: one point beyond 3 sigma, and 2 out of 3 points beyond 2 sigma
- Control charts didn't start until operators could construct and interpret them.
- Out-of-control situations were celebrated as opportunities to learn and improve.

We quickly learned that different groups came up to speed and different rates. Some groups took to SPC like ducks to water.

Others took to SPC like cats to water:

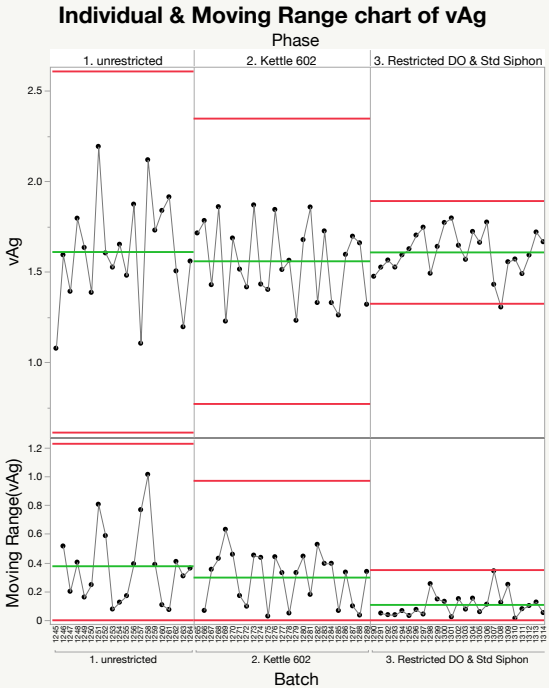
This is an early control chart for silver runtime.



Run Time Limit Summaries

Points plotted	Phase	LCL	Avg	UCL	Limits Sigma	Subgroup Size
Individual	1. unrestricted	295	308	322	Moving Range	1
Individual	2. Kettle 602	300	303	306	Moving Range	1
Individual	3. Restricted DO & Std Siphon	301	302	303	Moving Range	1
Moving Range	1. unrestricted	0	5	17	Moving Range	1
Moving Range	2. Kettle 602	0	1	4	Moving Range	1
Moving Range	3. Restricted DO & Std Siphon	0	0	1	Moving Range	1

In Phase 1, there were no restrictions on kettle or disc orifices. In Phase 2, each emulsion kind was restricted to one kettle. Silver runtime variability was reduced. In Phase 3, each emulsion kind was restricted to one kettle and one set of disc orifices. Runtime variability dropped again. Also siphoning went to a constant point rather than siphoning as much as possible. This change was after the silver flow had been completed and had no effect on silver runtime. It did have an effect on vAg as shown in the next plot.



vAg Limit Summaries

Points plotted	Phase	LCL	Avg	UCL	Limits Sigma	Subgroup Size
Individual	1. unrestricted	0.61	1.61	2.61	Moving Range	1
Individual	2. Kettle 602	0.77	1.56	2.35	Moving Range	1
Individual	3. Restricted DO & Std Siphon	1.32	1.61	1.89	Moving Range	1
Moving Range	1. unrestricted	0.00	0.38	1.23	Moving Range	1
Moving Range	2. Kettle 602	0.00	0.30	0.97	Moving Range	1
Moving Range	3. Restricted DO & Std Siphon	0.00	0.11	0.35	Moving Range	1

Several major improvements were accomplished in the next few months. The gel plant was unable to meet the specs for % phthallation with single lots. Gel lots were blended to achieve the proper % phthallation. Mixing a high % batch with a low % batch is not acceptable. If the lot with low % phthallation was too low, only part of that gel would coagulate in the wash step. The rest was lost when the supernatant liquid was siphoned off. A new spec required mixed batches must be within 1% of each other.

Significant reductions in Run time and vAg variability were accomplished as previously mentioned. The measurement of runtime was improved by using an automatic timer that started when the silver jar valve was opened and stopped when a sensor detected an empty line.

During an early trend chart phase, a lot was identified with unusual pH values during the washing step. The operator admitted that a mistake in the preparation of the ammonia jar caused a delay. Another operator indicated he had observed similar results on another batch of this emulsion kind a few weeks earlier. A review of the data sheets indicated there was also a delay in the start of that batch. Benchtop experiments demonstrated that holding the gel at the process temperature too long would cause a reduction in the buffering capacity of the gel. A time limit was specified for the main kettle. If the process had not started within the specified time, the kettle was emptied, and the contents were replaced. Dumping $200 worth of gel and salts was much better than adding silver worth tens of thousands of dollars and risking the discard of the completed batch. This improvement was made possible by an operator who was comfortable admitting a mistake. The author has worked in other situations where operators would routinely cover up mistakes for fear of punishment.

The team developed several aphorisms:

Consistency is often worth more than ultimate performance

Early successes are worth their weight in gold

Eliminate Fear (the 8th of W. Edwards Deming's 14 points)

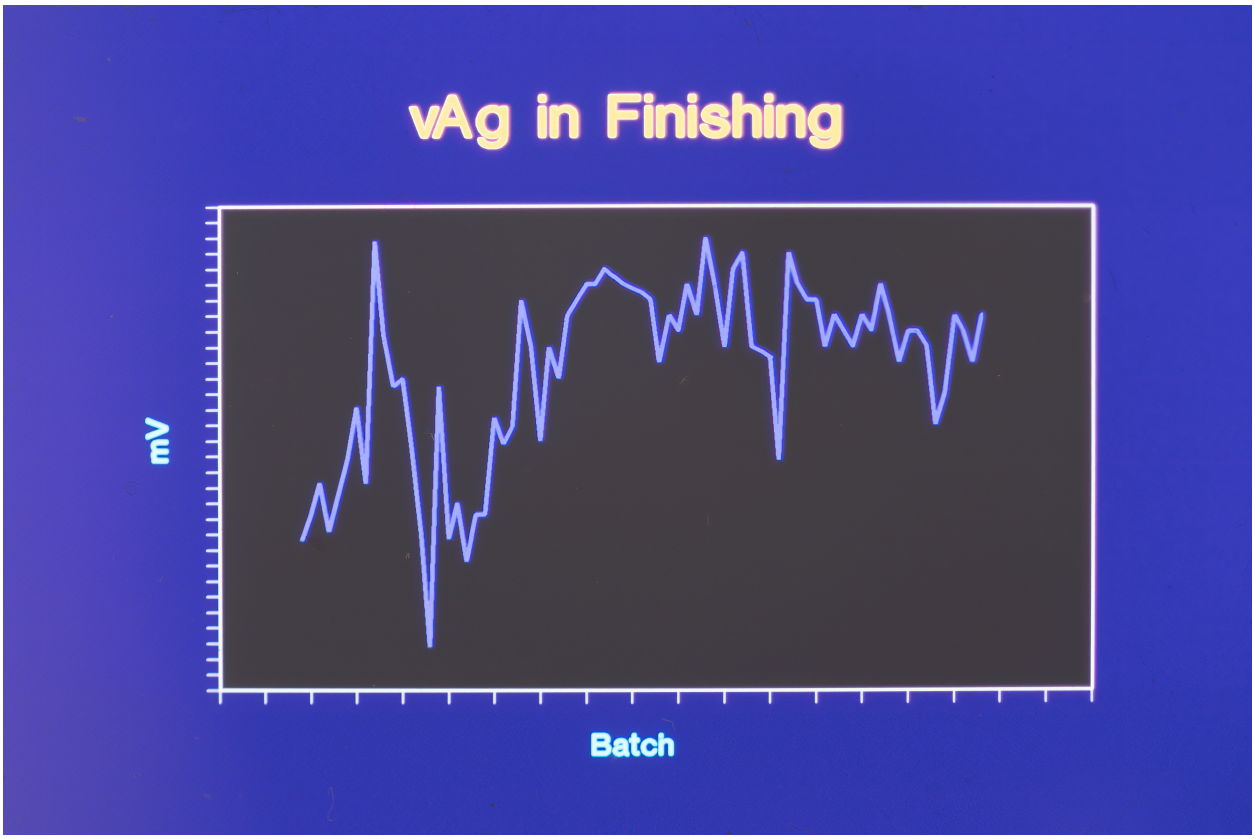
Overall Results

Each batch of emulsion is tested for photographic sensitivity. Lot-to-lot standard deviation for photosensitivity dropped from 10 units (1/3 stop) to about 1 unit which is the standard deviation of the test process. The standard deviation dropped by more than a factor of 10. The variance dropped by more than a factor of 100. Formula adjustments dropped drastically. Some products went from 6 changes per event to zero changes for 6 months. We had not dreamed of improvements of this magnitude.

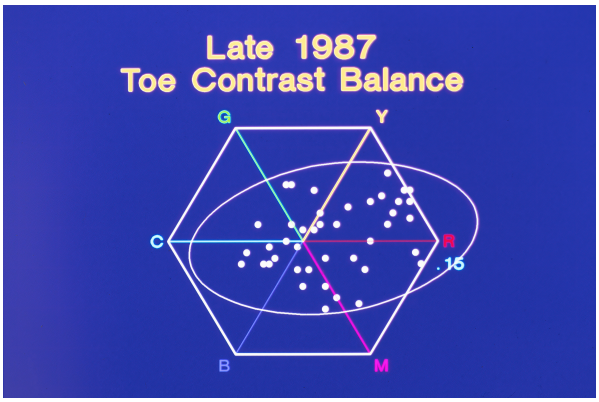
How do you do SPC when you make 6 batches/year?

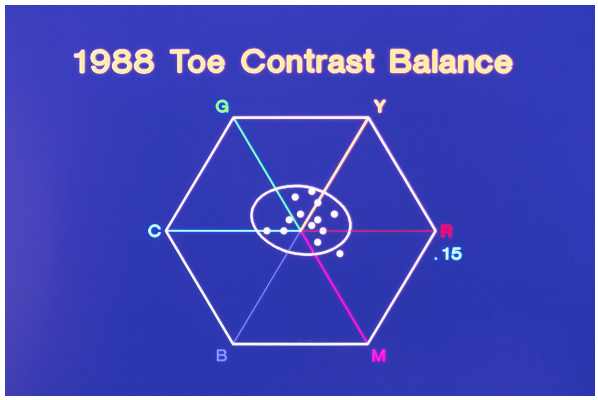
The author was responsible for Kodachrome 25 film, a venerable product that had once been a big runner that was assigned to large kettles. The market had moved to higher-speed products. Some of the emulsion kinds in Kodachrome 25 were only made 6 or 7 times a year. We adopted a process called creative swiping. The procedures that had aided the larger running Ektachrome films were used for the Kodachrome emulsions. These included limits on the range of gel lots that were blended to provide the correct % phthallation, a limit on gel preparation time, kettle restrictions, disc orifice restrictions, and siphoning to a designated level.

The variability of vAg in “Finishing” (the emulsion sensitization process) was reduced.



The most important parameter for color slide film is to match the contrast of all three color records. If the three contrasts didn’t match, there was no way for the photographer to correct the results in the years before Photoshop. This pair of plots show the improvement in contrast balance for Kodachrome 25.





These plots with blue backgrounds are scans of 35 mm slides that were part of an internal presentation at Kodak in 1988. These contain real data. Other plots and data tables used random number generators and the author's recollections.

Summation

- Use standard quality improvement tools.
- The technical staff should define the formulas and specifications.
- Operators should control the processes (with plenty of support and encouragement).
- KIS
- Celebrate opportunities to learn and make improvements.

Biography:

A chemical engineering degree from Rose-Hulman Institute prepared me for most aspects of an engineering career. Statistics was not one of them. Everything I've learned about statistics beyond calculating an average and a standard deviation has been learned on the job. My job titles always contained the word engineer.

Questions and comments are welcome using the contact information below. I will be traveling the week of the conference and may not respond immediately.

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